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# MUSCLE FATIGUE ASSESSMENT IN MANUAL HANDLING OF LOADS USING MOTION ANALYSIS AND ACCELEROMETERS

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# RESUMO

O termo fadiga muscular refere-se à diminuição transitória na capacidade de realizar ações físicas e à diminuição da força que os músculos envolvidos podem produzir. A fadiga muscular pode levar à perda de produtividade, originar erros humanos, ações inseguras e Lesões Músculo-Esqueléticas Relacionadas com o Trabalho (LMERT).

Os principais objetivos deste estudo consistiam em: a) Identificação de indicadores de fadiga muscular que possam ser listados e verificados num ambiente de trabalho real; b) Definir de um método de avaliação da fadiga muscular baseado em instrumentos de medição de movimento, para objetivar uma técnica de medição susceptível de ser aplicada num contexto laboratorial controlado e possível de ser replicada num ambiente de trabalho real, que englobará diversos efeitos sinérgicos.

Para cumprir os objetivos, foram elaborados 2 artigos. O primeiro artigo foi uma revisão sistemática realizada para resumir e analisar estudos sobre avaliação da fadiga muscular usando acelerómetros e análise de movimento. Foram incluídos 15 artigos na revisão sistemática. O segundo artigo engloba os estudos experimentais. No total, 13 voluntários preencheram um questionário, de forma a verificar a sua elegibilidade e realizaram um exercício de levantamento repetido de um disco de halteres de 2.5 kg numa elevação total de 0.5 m, até exaustão voluntária ou dor intensiva. Ao realizar o exercício, duas câmaras de vídeo registaram os movimentos realizados e as imagens foram posteriormente analisadas. Foi utilizada a análise de movimento como instrumento de trabalho. Devido a alguns contratempos, não foi possível utilizar acelerómetros, devido a problemas na calibração e obtenção de dados inconsistentes.

Os principais indicadores de fadiga muscular foram o aumento da inclinação para frente, micro expressões faciais, a mudança da estratégia de suporte da carga, segurar a carga mais próxima do peito durante a elevação e o aumento da velocidade de movimento excêntrico. Alguns voluntários sentiram desconforto nas pernas (pernas adormecidas), embora a experiência apenas tenha cansado diretamente os membros superiores. Os voluntários que praticam desporto regularmente aguentaram mais tempo na experiência e concluiu-se que fumar e o sedentarismo limitam a capacidade de prática de exercício físico. Os voluntários aumentaram a velocidade dos pulsos e dos cotovelos durante a experiência, especialmente no lado esquerdo do corpo. Verificou-se que metade dos voluntários teve movimentos menos fluidos durante a elevação, com valores de aceleração mais elevados numas partes e valores mais baixos noutras.

Concluiu-se que a fadiga muscular leva à variabilidade do movimento e que ocorrem adaptações musculares e cinemáticas para reduzir a carga nos músculos cansados. Os indivíduos alteraram significativamente os seus padrões cinemáticos em resposta à fadiga muscular. Para compensar a fadiga muscular, as pessoas adaptam a sua estratégia de trabalho, recrutam diferentes músculos e alteram as componentes cinéticas ou cinemáticas do movimento. A análise de movimento pode ser combinada com acelerometria para avaliar a fadiga muscular, registando mudanças nas acelerações e padrões de movimento.


**Palavras-chave**: Fadiga Muscular, Movimentação Manual de Cargas, Análise de Movimento, Variabilidade de Movimento, Movimentos Repetitivos

# ABSTRACT

The term muscle fatigue refers to the transient decrease in the capacity to perform physical actions and the decrease in the maximal force or power (velocity of muscle contraction) that the involved muscles can produce. Muscle fatigue can cause productivity loss, human errors, unsafe actions, injuries and work related musculoskeletal disorders (WMSDs).

The main objectives of this study were: a) Identification of muscle fatigue indicators that could be listed and checked in a real work environment; b) Definition of a muscle fatigue assessment method based on movement measuring instruments, in order to objectify a measurement technique susceptible to being applied in a controlled laboratory environment and possible to be replicated in a real work environment, which will encompass various synergistic effects.

To fulfill the objectives, 2 articles were elaborated. The first article was a systematic review performed to summarize and analyze studies concerning muscle fatigue assessment using accelerometers and motion analysis A total of 15 articles were included in the systematic review. The second article contains the experimental study. In total, 13 volunteers completed a questionnaire in order to verify their eligibility and performed a repetitive lifting exercise of a 2.5 kg dumbbell disc at a total elevation of 0.5 m until voluntary exhaustion or intensive pain. When performing the exercise, two video cameras recorded the movements performed and the images were subsequently analyzed. Movement analysis was used as a working tool. Due to some setbacks, it was not possible to use accelerometers due to problems in calibration and inconsistent data collection.

The main muscle fatigue indicators were increased forward bending, micro expressions, changing load support strategy, holding load closer to chest during elevation and increase in eccentric movement speed. Some volunteers felt discomfort in the legs (numb legs), although the experiment only directly fatigued upper limbs. Volunteers that practiced sports regularly lasted longer in the experiment and it was found that smoking and sedentarism limited the exercise capacity of some subjects. Volunteers increased the wrists and elbows velocity during the experiment, especially on the left side of the body. It was verified that half of the volunteers had less fluid movement during lifting, with higher acceleration values in some parts and lower values in others, translating into more impulsive movements.

It was concluded that muscle fatigue leads to movement variability and that muscular and kinematic adaptations occur to reduce the load on the fatigued muscles. Subjects altered their kinematic patterns significantly in response to muscle fatigue. To compensate muscle fatigue, people adapt their working strategy, recruit different muscles and change kinetic or kinematic components of the movement. Motion analysis can be combined with accelerometry in order to assess muscle fatigue, by noticing changes in accelerations and movement patterns.


**Keywords**: Muscle Fatigue, Manual Handling of Loads, Motion Analysis, Movement Variability, Repetitive Movements

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# LIST OF ABBREVIATIONS AND ACRONYMS

3DSSPP – 3 Dimensional Static Strength Prediction Program

AMG – Acoustic Myography (AMG)

BMI – Body Mass Index

DLT – Direct Linear Transformation

EMG – Electromyography

EUROFUND – European Foundation for Improvement of Living and Working Conditions

EWCS – European Working Conditions Survey

F – Female

ISO – International Organization for Standardization

KIM – Key Indicator Method

LMM – Lumbar Motion Monitor

M – Male

MAC – Manual Handling Assessment Charts

MHL – Manual Handling of Loads

MMG – Mechanomyography

NIRS – Near-infrared Spectroscopy

OWAS – Ovako Working Posture Analyzing System

PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analyses

REBA – Rapid Entire Body Assessment

ROM – Range of Motion

RPE – Ratings of Perceived Exertion

RULA – Rapid Upper Limb Assessment

sEMG – Surface Electromyography

SMG – Sonomyography

WRMSD – Work-Related Musculoskeletal Disorders

# PART 1

# 1 INTRODUCTION

## 1.1 General Introduction

Despite the large existing mechanization in industries, there are tasks where the work done by man is irreplaceable, being an example the manual handling of loads (MHL), which consists of any of the following activities: lifting, holding, putting down, pushing, pulling, carrying or moving of a load (Monteiro, 2014; EU-OSHA, 2007).

Muscle fatigue refers to the transient decrease in the capacity to perform physical actions and the decrease in the maximal force or power (velocity of muscle contraction) that the involved muscles can produce (Enoka, et al., 2008). A significant level of muscle fatigue can cause productivity loss, human errors, unsafe actions, injuries and Work related Musculoskeletal Disorders (WMSDs) (Sluiter et al. 2003; Toole 2005; Huang and Hinze 2006; Hallowell 2010).

The repetition of movements, efforts and poor body posture while working, can lead to Work-related Musculoskeletal Disorders (WMSDs), which are a set of inflammatory and degenerative diseases of the locomotor system, which may affect the muscles, tendons, ligaments, joints, cartilage, bones, spinal cord and peripheral nerves. These practices have become a major cause of injuries in the industries, bringing consequences for the worker (muscle injuries and psychological impacts) as well as for organizations, due to loss of production, absenteeism or compensations. This denotes that this is a problem in terms of safety and occupational health, as well as social and economic (Pombeiro, 2011; Santos, 2009).

It is important to consider several risk factors associated with these injuries, such as load characteristics, the performed task, the person itself, the work environment and work practices. These risk factors consist in all factors that cause a negative effect on the worker, like a disease or injury. They are usually separated in three groups: physical, individual and organizational/psychosocial. The physical factors include force application, vibrations, manual handling of loads, repetitive movements and static postures. Individual factors include age, sex, weight, anthropometric characteristics and health condition. Organizational/psychosocial factors include intensive work rhythm, monotonous tasks, time pressure and productivity requirements (Gonçalves, 2014).

To manage and control these ergonomic risks, several methods were developed for exposure assessment and estimate the risk of injury, such as self-assessment questionnaires and checklists, observational methods (like RULA, REBA and OWAS methods), direct/biomechanical methods (using electronic equipment such as Force Sensitive Resistors and Accelerometers), a combination of observational and direct methods, among others. (Monteiro, 2014; Santos, 2009). Although observational methods are easy to use and interpretate, they have some disadvantages, such as the fact that they are very subjective and depend on the notions and experience of the observer. As for the direct methods, they are quite complex and demand the use of electronic equipment, which requires greater investment, maintenance and highly skilled technicians. The creation of a method that combined both strategies would be very helpful, combining the strengths of each one and increasing the reliability and effectiveness of future measures.

Motion analysis is highly used in sports biomechanics, in order to study and analyze human movement patterns, to improve performance and reduce the risk of injury. There are two fundamentally different approaches to experimental movement analysis in sports, namely qualitative analysis and quantitative analysis. Qualitative analysis describes and analyses movements non-numerically, by seeing movements as 'patterns'. It doesn't require expensive equipment, is field-based and not laboratory-based and when done properly is highly systematic. Quantitative analysis describes and analyses movement numerically, with biomechanical data and using equipment like marker-tracking systems and force or pressure plates. A third approach that fits between the two is called semi-quantitative analysis, that combines both perspectives, that is, analyzes the movements 'patterns' and quantifies them with the help of equipment attached to the subject body, like accelerometers and force sensors (Bartlett, 2007)

## 1.2 Statistics

The sixth European Working Conditions Survey (EWCS) provides an overview of working lives through the focus of job quality and gathers detailed information from nearly 44.000 workers across Europe. The European Foundation for Improvement of Living and Working Conditions (EUROFUND) developed seven indices representing different dimensions of job quality, namely (EUROFUND, 2016):

- **Physical environment:** Posture-Related (ergonomic); Ambient (vibration, noise, temperature); Biological and Chemical;
- **Work intensity:** Quantitative demands; Pace determinants and interdependency; Emotional demands;
- **Working time quality**: Duration; Atypical Working Time; Working time arrangements; Flexibility;
- **Social environment:** Adverse social behavior; Social Support; Management quality;
- **Prospects:** Cognitive dimension; Decision latitude; Organizational participation; Training;
- **Skills and discretion:** Employment status; Career prospects; Job Security; Downsizing;
- **Earnings**

The indices are measured on a scale from 0 to 100, (except the earnings index, that is measured in euro) and the higher the index score, the better the job quality (except for work intensity, where the reverse is the case) (EUROFUND, 2016).

Three combined indices were constructed for the physical environment dimension (EUROFUND, 2016):

**Posture-related (ergonomic) risks:** This index measures exposure to vibrations, tiring positions, lifting people, carrying heavy loads and repetitive movements. According to EUROFUND, these are the most prevalent risks in Europe and include the risks that can play a role in the common workplace complaint, musculoskeletal disorders.

**Ambient risks:** This index measures exposure to vibrations, noise, and high and low temperatures.

**Biological and chemical risks:** This index measures exposure to inhaling smoke and toxic vapours and handling chemical products and infectious materials.

**Figure 1** illustrates levels of exposure to the three forms of risk by country, ordered by exposure to posture-related risks. Posture-related risks are the most prevalent risk in every country. Portugal has one of the lowest levels of exposure to ambient risks and biological and chemical risks, but one of the highest in posture-related (EUROFUND, 2016).

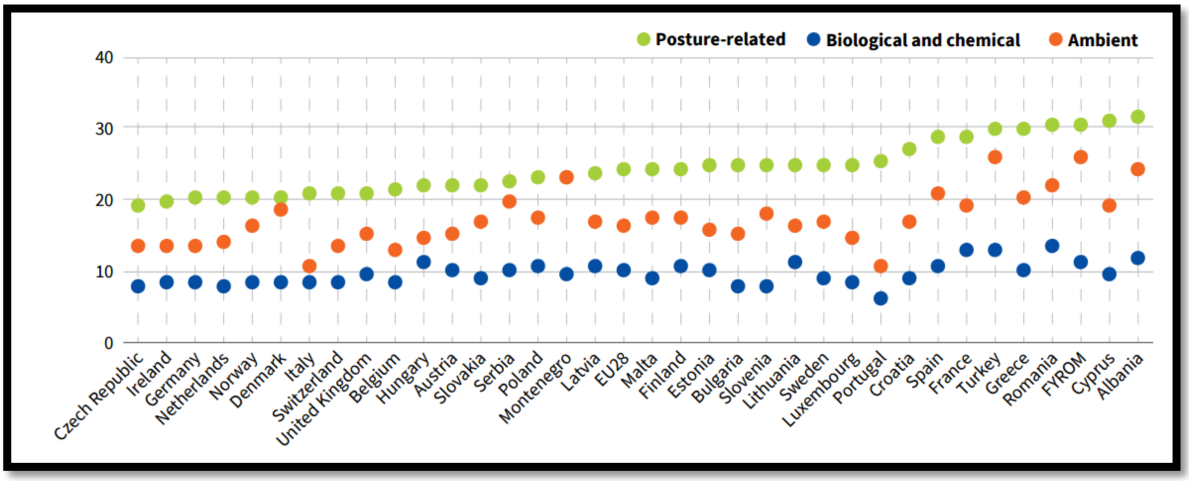


**Figure 1** – Exposure to three forms of risk indices (0-100), by country

Analyzing **Figure 2**, that shows the evolution of the physical environment index from 2005 to 2015, there are improvements since 2005 in most European countries, with the exception of France and the United Kingdom. Portugal, Greece, Hungary and Croatia have the most notable improvements, the first two with a seven-point increase and the other two with six points (EUROFUND, 2016).

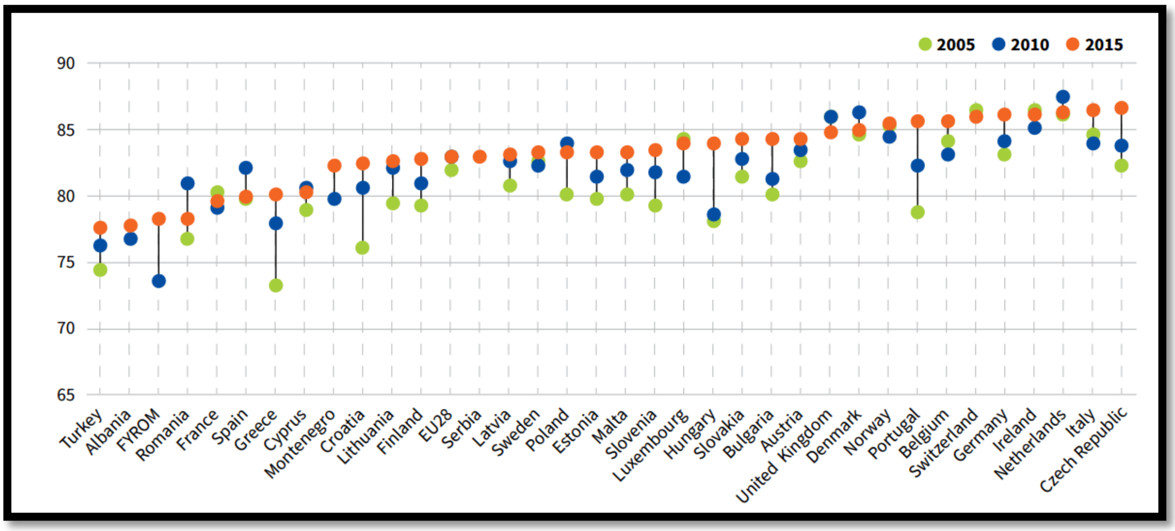


**Figure 2** – Physical environment index (0-100), by country, 2005-2015

Analyzing **Table 1**, the 'lifting or moving people' is the only posture-related risk among those included in the EWCS that is shown to be on the increase. In 2015, 'Repetitive hand or arm movements' has the highest percentage, with 62% of workers, followed by 'Tiring or painful positions' with 44% and 'Carrying or moving heavy loads' with 32%.

**Table 1** – Physical environment index: proportion of workers in EU28 (%), 2005-2015

| | 2005 | 2010 | 2015 |
|---|---|---|---|
| Tiring or painful positions | 46 | 46 | 44 |
| Lifting or moving people | 8 | 9 | 10 |
| Carrying or moving heavy loads | 35 | 34 | 32 |
| Repetitive hand or arms movements | 62 | 63 | 62 |

The physical environment index has risen marginally over the years, from 82 in 2005 to 83 in 2010 to 84 in 2015, signifying decreasing exposure to physical risks.

Women have lower levels of exposure to all three types of physical risk when compared to men, but for some specific risk, shown in **Figure 3**, that is not the case. Repetitive hand and arm movements are the most prevalent posture-related risk and are almost equally reported by men and women (61% and 62%, respectively). Analyzing **Figure 3**, 31% of the men are exposed all or most of the time, while women have 34% (more 3%). The other posture related-risk where women have higher levels of exposure is lifting and moving people, with 2% of men exposed all or most of the time compared to 6% of women. On the other side, carrying or moving heavy loads is reported by 12% of men all or most of the time and women only have 6%.

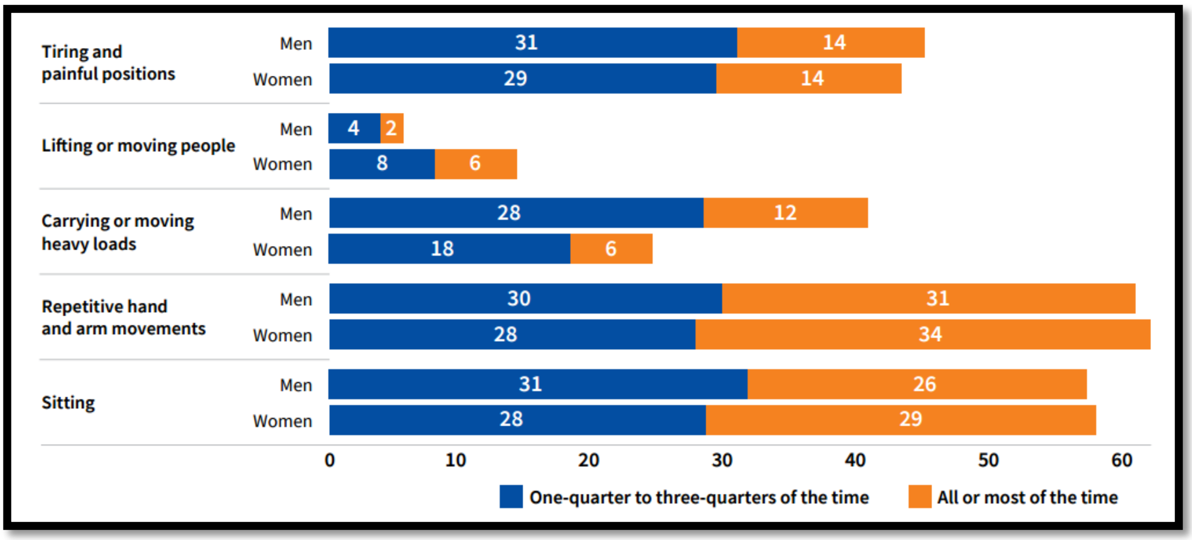


**Figure 3 –** Exposure to different posture-related risks, by sex, EU28 (%)

## 1.3 Legal and Regulatory Framework

Relatively to Legislation associated with this issue, one can highlight Directive 90/269/ EEC of 29 May 1990 on the minimum safety and health requirements concerning the manual handling of loads entailing risks for workers. In Portugal, Decree-Law n.º 330/30 of 25 September transposes Directive 90/269/EEC into national law. According to it, as general prevention measures, the employer must adopt appropriate work organization measures or use the appropriate means, such as mechanical equipment, in order to avoid manual handling of loads by workers. If it can't be avoided, the employer must ensure that it is as safe as possible. The employer must carry out an assessment of the reference elements for the manual handling of loads and the safety and health conditions of that type of work, taking into account: a) The load characteristics; b) The required physical effort. When the evaluations of the reference elements reveal a risk to the health and safety of workers, the employer must identify the causes and individual risk factors, including physical disability and take appropriate corrective measures. Workers must be consulted when implementing the measures. The employer must provide information to exposed workers on: a) the potential health risks arising from improper manual movement of loads; (B) the maximum weight and other characteristics of the load; C) the center of gravity of the load. Workers must receive appropriate training.

The classification of the methodologies that identify and assess the risks of MHL tasks was established according to the level of intervention and increased specificity of the methodologies, having been grouped into three different levels (Simões, 2015):

**Level I - Risk Identification:** Level I methodologies are checklist-type tools that are intended to describe the MHL tasks, the physical conditions and requirements of the MHL, and the identification of the risk associated with the MHL tasks according to the European Directive 90/269/EEC. However, these methodologies do not consider any individual risk factor, such as the worker's age or body weight. Two examples are the Committee of Senior Labour Inspectors

(SLIC) Checklist and the National Institute for Occupational Safety and Health (NIOSH) Checklist.

**Level II - Risk Assessment:** Level II methodologies assess the inherent risk of MHL tasks and are generally based on three approaches: biomechanical, psychophysical and physiological. The biomechanical approach involves the measurement of kinematics (speed, acceleration) and biomechanical forces imposed on the musculoskeletal system. The psychophysical approach is associated with the perception of workers' MHL capacity. This approach establishes limits of maximum load weight considered acceptable. The physiological approach studies the physiological requirement of the MHL task and compares it with the physiological (limit) capacity that the worker has to perform it. Some examples are the NIOSH Lifting Equation, Liberty Mutual Tables, Manual Handling Assessment Charts (MAC) and Key Indicator Method (KIM).

**Level III - Risk assessment for complex and/or specific problems:** These methodologies allow assessing the risk of extraordinary and specific problems - which cannot be assessed by level II methodologies. The complexity and effort required to apply these methodologies is usually high. Some examples are Electromyography (EMG), Lumbar Motion Monitor (LMM) and 3 Dimensional Static Strength Prediction Program (3DSSPP).

Internationally there are the ISO 11228 standards, under the general title: Ergonomics – Manual handling, divided into 3 parts (ISO 11228-1:2003 – Lifting and Carrying, ISO 11228-2:2007 – Pushing and Pulling and ISO 11228-3:2007 – Handling of low loads at high frequency) (Monteiro, 2014). The first part specifies recommended limits for manual lifting and carrying while taking into account the intensity, the frequency and the duration of the task. It provides a step-by-step approach to estimating the health risks of manual handling and carrying. At each step, recommended limits are proposed (ISO, 2003). The second part provides two methods for identifying the potential hazards and risks associated with whole-body pushing and pulling. It proposes recommendations for reducing the risk of injury or ill health (ISO, 2007a). The third part establishes ergonomic recommendations and provides guidance on the identification and assessment of risk factors commonly associated with handling low loads at high frequency (ISO, 2007b).

As previously said, the creation of a method that combined observational and direct methods, as well as different methodologies that identify and assess the risks of MHL, is of great importance. A systematic review of existing studies concerning muscle fatigue assessment using accelerometers and motion analysis was performed and is presented in Chapter 2.

## 1.4 Thesis Structure

This thesis is divided in 5 chapters:

- Chapter 1 includes a brief introduction to muscle fatigue, Work-related Musculoskeletal Disorders, risk factors and existing methods that assess and estimate risk of injury. Relevant statistics from the sixth European Working Conditions Survey is analyzed, as well as legal and regulatory framework;
- The state of the art, presented in Chapter 2, consists in a systematic review according to PRISMA Statement. An explanation of the methodological procedures of the bibliographic research is presented. The selected articles were analyzed, namely the country, sample, muscle group, performed task, fatigue measurement method, equipment, software, and main conclusions. This review helped to conceptualize the practical experiment, the equipment and the topics that should be addressed in the experimental study.
- Chapter 3 is a brief chapter that explains how the main conclusions of the systematic review helped conceptualize the practical experiment, why certain decisions and choices were made and what ideas were gathered from previous studies and implemented, such as equipment and methodology; The two main objectives of the study are identified.
- The equipment, procedure, results and discussion of the experimental study are presented in Chapter 4. The participant selection criteria are explained and their characteristics are presented. The equipment used, the procedure used to create the 3D model and analyze the recordings, the experimental procedure and statistical analysis are presented. The results include the questionnaire results, a list of muscle fatigue indicators demonstrated by the volunteers and the statistical results, regarding the position, velocity and acceleration of 3 joints: wrists, elbows and shoulders. Strengths and limitations of the methodology are presented.
- Chapter 5 includes the main conclusions of the thesis, as well as some future work suggestions.

# 2 STATE OF THE ART – MUSCLE FATIGUE ASSESSMENT IN MANUAL HANDLING OF LOADS USING ACCELEROMETERS AND MOTION ANALYSIS: A SYSTEMATIC REVIEW

# Muscle Fatigue Assessment in Manual Handling of Loads using Motion Analysis and Accelerometers: A Systematic Review

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ABSTRACT: Muscle fatigue can cause productivity loss, human errors, unsafe actions, injuries and work related musculoskeletal disorders (WMSDs). To compensate muscle fatigue, people adapt their working strategy, changing movement patterns, recruiting different muscles and changing kinetic or kinematic components of the movement (like joint angles and velocities). This review, according to PRISMA Statement, was performed to summarize and analyze studies concerning muscle fatigue assessment using accelerometers and motion analysis. It was based on relevant articles published in 6 databases, namely Academic Search Complete, Inspec, PubMed, Science Direct, Scopus and Web of Science. A total of 15 articles were included in the systematic review. The following topics were analyzed: muscle groups evaluated, the tasks performed by the volunteer subjects, the assessment methods applied and the equipment and software used. Similar conclusions were obtained, regarding movement variability, muscular adaptations and changes in movement strategies, due to fatigue.

**Keywords:** Accelerometers, Manual Handling of Loads, Movement Variability, Repetitive Movements, Biomechanics.

**Presentation Preference:** Oral

## 2.1 INTRODUCTION

The term muscle fatigue refers to the transient decrease in the capacity to perform physical actions and the decrease in the maximal force or power (velocity of muscle contraction) that the involved muscles can produce (Enoka et al., 2008).

Mechanisms responsible for fatigue may be central (alterations in the central nervous system and/or neuromuscular junction) or peripheral (alterations in the muscle fiber) (Davis et al., 2010).

It can be localized in a specific muscle group (Corbeil et al., 2003) or widespread over several muscle groups (Bove et al., 2007).

Muscle Fatigue can be categorized as one of the symptoms of blood occlusion, because limited blood flow delivers insufficient oxygen and nutrients, alongside inadequate removal of metabolic waste products, causing lactate concentrations to rise (Oyewole, 2014).

Muscle fatigue can be divided in 3 stages: Non-Fatigue (the fresh muscle is able to exert its maximum force), Transition-to-Fatigue (once the fresh muscle starts to fatigue, new recruitment of muscle fibers occurs) and Fatigue (the onset of fatigue during a muscle contraction) (Al-Mulla et al., 2011). The Transition-to-Fatigue stage can be extended by practicing proper work/rest time ratio and controlling the lifting variables when performing manual handling of loads, that consist in any of the following activities: lifting, holding, putting down, pushing, pulling, carrying or moving of a load (animate or inanimate) (Halim et al., 2014). A significant level of muscle fatigue can cause productivity loss, human errors, unsafe actions, injuries and work related musculoskeletal disorders (WMSDs) (Sluiter et al. 2003; Toole 2005; Huang and Hinze 2006; Hallowell 2010).

During repetitive and fatiguing work, the musculoskeletal system adapts and uses momentary muscle substitution patterns, which result in more variable and less coordinated movements (Mehta et al., 2015). Other important aspect that allows this movement variability is the biomechanical redundancy of the upper limb multi-joint kinematic system (Madeleine, 2010). This way, individuals may exploit redundant degrees of freedom to counteract the effects of muscle fatigue (Srinivasan and Mathiassen 2012). The workers experience also plays a role, as demonstrated by Authier et al. (1996), were distinct lifting techniques were used by experienced workers in transferring boxes and these techniques were tested and reported to reduce back loading. A study of dynamic lifting conducted by Chen (1999), revealed that the lifting range differed significantly when participants felt fatigue in the upper limbs and that they used increasingly stooped and accelerated techniques at the beginning of the lift, followed by stiffening of the arms at the end of the lift.

The selection of volunteer subjects has to comply with certain criteria. It is important that the subjects are healthy, because any diseases or injuries may influence muscle performance and lead to inconsistent findings. Smoking and alcohol consumption also influence the results, alongside age and gender differences (Al-Mulla et al., 2011).

The assessment methods can be classified into invasive and non-invasive. Some examples of invasive methods are: blood lactate level, blood oxygen level, pH of muscle and needle electromyography (EMG). Some examples of non-invasive methods are: surface electromyography (sEMG), near-infrared spectroscopy (NIRS), mechanomyography (MMG), acoustic myography (AMG) and sonomyography (SMG) (Bhat et. al., 2016).

A recent review, performed by Srinivasan and Mathiassen (2012) concluded that motor variability is a relevant issue in an occupational context and that there is a great need for studies of motor variability. They suggest future research in creating methods to assess motor variability and study the relationship with occupational tasks and outcomes like fatigue and performance.

The main objective of this study involves the definition of a muscle fatigue assessment method based on movement measuring instruments, specifically accelerometers and motion analysis, in order to objectify a measurement technique susceptible to being applied in a real work environment. A systematic review was performed, to review the literature concerning muscle fatigue assessment using accelerometers and motion analysis, in order to analyze what muscle groups were evaluated, the tasks performed by the volunteer subjects, the assessment methods used, the equipment and software used, and collect the most important conclusions, relevant to the present study.

## 2.2 METHODS

### 2.2.1 Search Strategy

The search was conducted through 6 electronic databases, namely: Academic Search Complete, Inspec, PubMed, Science Direct, Scopus and Web of Science.

The systematic review focused on literature that addresses muscle fatigue assessment, using accelerometers and motion analysis, especially applied to upper limbs. Thus, the selected keywords used in the research had to be related to accelerometers, upper limbs, movement and kinetics. In order to assess other possible methods that have been applied, a couple of more generic keywords were used, regarding muscle fatigue determination and the evaluation over time. Finally, a relation between fatigue and musculoskeletal disorders had to be analyzed, more specifically in a workplace environment.

The search terms were as follows:”Muscle Fatigue” combined with “Accelerometer”, “Repetitive Work”, “Upper Limbs”, “Force Sensor”, “Postural Control”, “Lifting”, “Tracking”, “Movement Variability”, “Forearm Muscles”, “Repetitive Lifting”, “Determination”, “Manual Handling”, “Reflex”, “Biomechanic”, “Arm Movement”, “Kinetic”, “Workplace” and “Musculoskeletal disorders”. A total of 4760 items were found, using these keywords only (371 from Academic Search Complete, 210 from Inspec, 483 from PubMed, 317 from Science Direct, 2344 from Scopus and 1035 from Web of Science).

### 2.2.2 Screening Criteria

The search was initially conducted by inserting the keywords and selecting, when possible, “Article title, Abstract, Keywords”. The selected years were from 2010 to 2016 and the selected document type were articles, reviews and journal articles. Only the English language was considered. A total amount of 1955 items were gathered, using this search filters, meaning 2805 were excluded.

Since a lot of these items were duplicates, these had to be removed and counted, before continuing the screening criteria. A total of 997 duplicates were removed, resulting in a final value of 958 records screened. The next step in the screening had the following procedure:

a) Title and Abstract were analyzed; Studies were automatically excluded if one of these conditions were met: 1) studies related to muscle rehabilitation; 2) studies applied to people with injuries/disorders/diseases; 3) studies applied to elders; 4) studies related to prosthetics; 5) studies related to sports like running, football, cycling, where lower limbs are predominantly used.

b) the full text article was retrieved and considered. Whenever the title and abstract weren't enough to determine if the selection criteria were met, the article proceeded to the next step. If the article couldn't be retrieved, it was also excluded.

This procedure led to a total of 51 articles, meaning 907 articles were excluded.

### 2.2.3 Eligibility Criteria

Studies were included if the following conditions were met: a) Muscle fatigue development in upper limbs (forearm, arm and shoulder muscles) and torso (2 excluded); b) Experimental evaluation based on movement (7 excluded); c) Well defined sample/participants (age, body mass and height) (7 excluded); d) Sample without any injuries/chronic pain (1 excluded); e) Studies not comparing different tools to assess muscle fatigue (4 excluded); f) Studies not validating methods or related to virtual simulation (3 excluded); g) Studies not assessing fall risk (2 excluded); h) Studies not related to assembly/pegboard or similar activity (6 excluded); i) Studies not evaluating task rotation effect on fatigue (2 excluded); j) Studies performed in a workplace/occupational environment (2 excluded); This eligibility criteria led to a total of 15 articles, meaning 36 articles were excluded. **Figure 1** displays the flowchart of the systematic review stages, according to PRISMA statement.

All selected articles have ethical considerations: informed consent obtained on human subjects and the protocol was approved by an ethical committee.

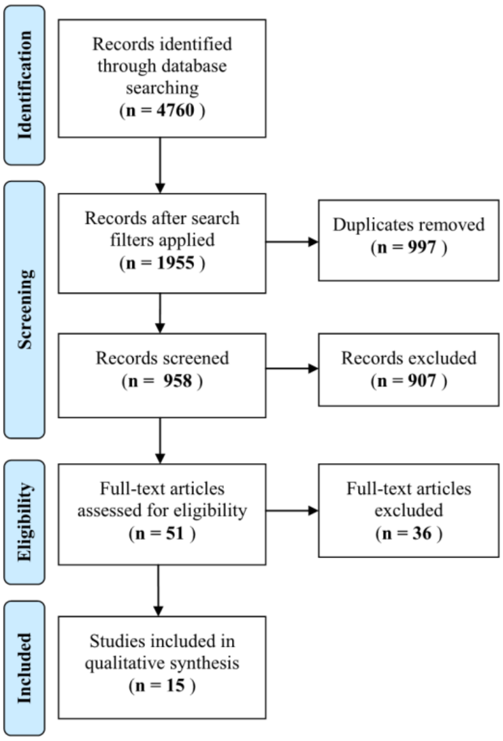


**Figure 1 –** Systematic Review Stages

## 2.3 RESULTS AND DISCUSSION

The resulting 15 articles and relevant information are presented in **Table 1**.

Analyzing the countries of each study, 8 were performed in the United States of America, 2 in Canada, 2 in France, 1 in Germany, 1 in Greece and 1 in New Zealand.

## Table 1 – Selected articles (most recent to older)

| Reference | Sample | Muscle Group | Task | Fatigue Measure | Equipment and Software | Conclusions |
|---|---|---|---|---|---|---|
| (Brown et al., 2016); Germany | 20 participants (60% male, 25.1 ± 1.5 years, 73.9 ± 14.5 kg, 167.5 ± 40.2 cm, 6.7 ± 5.4 years of strength training experience). | Biceps Brachii | 3 sets of 3 exercises (biceps curl, bench press, leg extension) with 50% (12 repetitions), 75% (12 repetitions) and 100%-12 Repetition Maximum (RM). 3 min of rest between the sets. | sEMG; Accelerometry; | 3D accelerometer; Linear Potentiometer; MatLab; | Higher movement variability was seen regarding repetition duration and range of motion (ROM) |
| (McDonald et al., 2016) Canada | 12 right-hand dominant men (20–24 years, 76.5 ± 8.5 kg, 177.9 ± 6.8 cm). | Anterior Deltoid, Posterior Deltoid, Latissimus Dorsi, and Serratus Anterior Muscles | Four tasks: (1) handle pull (2 kg, 10 repetitions), (2) cap rotation (6 revolutions – 3 clockwise, 3 counter-clockwise), (3) drill press (50% of maximum in the anterior axis, 10 s), (4) handle push (2 kg, 10 repetitions). | sEMG | Passive motion capture system using eleven 4-megapixel resolution cameras; Reflective markers; Visual-3D; | Participants maintained performance via kinematic and muscular adaptations, such as reduced glenohumeral flexion and scapular rotation. |
| (Mehta et al., 2015) United States of America | 17 healthy volunteers, 13 males and 4 females between the ages of 18 and 32 (M = 21.3 years, SD = 4.1 years). Mean height and weight of the participants were 176 cm (SD = 7 cm) and 79.7 kg (SD = 11.2 kg). | Erector Spinae | Repetitive asymmetric lifting for 60 min (10 lifts/min). | NIRS | 2-channel INVOS 4100 Cerebral Oximeter; Magnetic Motion Capture System; Bertec force plates; Dynamometer; Borg Scale; | Increases in the overall lift duration, peak forward bending motion and three-dimensional movement velocities of the spine, along with a decrease in the lateral bending moment. |
| (Boocock et al., 2015) New Zealand | 28 adult males participated in the study. 14 were aged between 20 and 31 years (M = 24.4 years (SD = 3.5 years), and made up the group of ‘younger’ adults. The ‘older’ group consisted of 14 participants aged 43–54 years (M= 47.2 years (SD = 3.4 years)). | Erector Spinae | Participants lifted and lowered a box weighing 13 kg at a frequency of 10 lifts/min. | sEMG | 9 camera motion analysis system; Retro-reflective markers; 2 AMTI Force Platforms; Metronome; Visual 3D; LabView; | Age was a factor influencing postural kinematics and kinetics during a repetitive manual handling task. |

## Table 1 – Selected articles (continuation)

| Reference | Sample | Muscle Group | Task | Fatigue Measure | Equipment and Software | Conclusions |
|---|---|---|---|---|---|---|
| (Cowley et al., 2014)<br><br>United States of America | 20 subjects (9 female, 11 male). Their mean ± SD age, body mass, and height were 25 ± 2.2 years, 71.2 ± 14.9 kg, and 1.71 ± 0.10 m, respectively. | Shoulder Flexors, Pectoralis major, Upper trapezius, Deltoids, Biceps, Triceps, Flexor Carpi Radialis, and Extensor Carpi Radialis Longus. | Task similar to sawing for 5 continuous minutes both before and after completing a protocol that either induced widespread fatigue or localized fatigue. | sEMG | 8-camera Vicon-612 motion capture system; Markers; Metronome; Dynamometer; Borg Scale; | Localized and widespread muscle fatigue affected movement differently. Local fatigue may reduce the available motor solutions and therefore cause greater movement reorganization than widespread fatigue. |
| (Mehta et al., 2014)<br><br>United States of America | 17 volunteers, 11 males and 6 females (mean = 21.7 years, SD = 5.9 years). Mean height and weight of the participants were 1.75m (SD = 0.09 m) and 79.7 kg (SD = 19.1 kg). | Erector Spinae | Grasp the handles and repetitively lift a box from a conveyor (0.25m above the floor) and place it to the conveyor located to their left side (0.86m above floor) without moving their feet and incorporating a stoop posture. | NIRS | 2-channel INVOS 4100 Cerebral Oximeter; Magnetic Motion Capture System; Bertec force plates; Dynamometer; Borg Scale; | Increases in the amount of forward bending, the extension velocity and the lateral bending velocity of the spine. |
| (Dong et al., 2014)<br><br>Canada | 17 subjects (10 males and 7 female): age 30.47 ± 6 years; body mass 71.71 ± 16.81 kg; body height 172.82 ± 11.25 cm; and body mass index (BMI) 23.86 ± 4.03 kg/m. | Biceps Brachii, Anterior Deltoids, and Triceps Brachii. | In Experiment 1, the subjects were asked to hold their self-body weight with both arms for a period of time (dip start position training); In Experiment 2, the subjects were asked to periodically lift a weight (10 kg for males, and 6 kg for females) with their right arm. | sEMG; Accelerometry | Triaxial accelerometer; MatLab; Video Camera; | The sEMG signal and corresponding acceleration signal were filtered and re-sampled so that both signals had the same sampling rates. The filtered acceleration signal was used to recognize periodic movements. If periodic movements were detected, the filtered sEMG signal was segmented and connected to form a new sEMG signal. |
| (Monjo et al., 2014a)<br><br>France | 15 subjects (11 men and 4 women, age 22.7±0.5 years; height 1.75±0.03 m; weight 71.4±2.8 kg). | Anterior Deltoid, Posterior Deltoid | Perform two different focal movements (arm flexions or extensions), depending on the random presentation of color word-color associations (Stroop-like task). | sEMG | 3 camera motion analysis system; Force Platform; Force Sensor; DColl Software; Force Transducer; Marker; | The fatigue protocol resulted in significant alterations of arm flexion peak accelerations. |

## Table 1 – Selected articles (continuation)

| Reference | Sample | Muscle Group | Task | Fatigue Measure | Equipment and Software | Conclusions |
|---|---|---|---|---|---|---|
| (Lee et al., 2014)<br><br>United States of America | 6 experienced and 6 novice workers completed the study, with 5 males and 1 female in each group.[ Novice Group: Age mean =26,8± 7,1; Height mean = 1,80 ± 0,09; Body mass mean=80,2 ± 10,9] [ Experienced group: Age mean =28,3 ± 6,9; Height mean = 1,73 ± 0,10; Body mass mean=86,6 ± 14,6] | Body Parts: Torso, Pelvis, Shin, Head, Upper Arm, Lower Arm | Workers completed 185 cycles of repetitive, asymmetric lifts/lowers. A wooden box was used (33 x 59 x 24 cm), which had cut-out handles at 21 cm from the bottom and was loaded to equal 15% of individual body mass. | Torso kinematics/kinetics, linear/angular momenta and Lyapunov exponents | Dynamometer; Reflective Markers; 7 camera system; Force Platforms; 3D linked-segment model with 15 body segments (and a box); Borg Scale; | Fatigue induced changes in movement strategies. Novices and experienced workers adapted to fatigue differently. |
| (Monjo et al., 2014b)<br><br>France | 18 subjects (14 men and 4 women, age 21.3 ± 0.5 years; height 1.74 ± 0.02 m; weight 70.14 ± 2.3 kg). | Anterior Deltoid, Biceps Femoris, Erector Spinae, Rectus Femoris | Arm-raising movements in a standing posture at a maximal velocity before and after a fatiguing procedure involving focal muscles. Muscular fatigue was induced by achieving intermittent isometric contractions at 70 % of MVF. | sEMG | Force Platform; Potentiometer; DColl software; Force transducer; | Following the fatiguing procedure, acceleration peaks of the arm movement decreased by ~27 %. |
| (Ferguson et al., 2013)<br><br>United States of America | 10 subjects (3 females and 7 males). The average age of the participants was 43.1 years with a standard deviation of 6.1 years. The average height and weight of the participants was 176.0 cm (SD = 10.6) and 82.6 kg (SD = 20.6), respectively. | Biceps, Anterior Deltoid, Trapezius, Middle Deltoid | Repetitive exertions similar to motions found in automobile assembly tasks. There were three independent variables: shoulder angle, frequency, and force. | sEMG; NIRS; | INVOS 4100 Cerebral Oximeter; Force transducer; Goniometer | Significant decrease in trapezius muscle percentage change in oxygenated hemoglobin as a function of shoulder angle. At faster repetition levels, the influence of shoulder angle was greater. |
| (Spyropoulosa et al., 2013)<br><br>Greece | 9 female volunteers with mean age 24 ± 2 years, mean body height 162 ± 5 cm and mean body weight 67 ± 7 kg. | Anterior Deltoid | Repetitive lifting using 2 different ranges (LR1, LR2). LR1 was lifting from the floor to a 176 cm height shelf. LR2 was lifting from a 102 cm height shelf to a 176 cm height shelf. | sEMG; | Two-dimensional biomechanical model of the upper limb; Video camera; Reflective Markers; Logger PRO software; Max PRO software; Borg Scale; | Fatigue accumulation strongly depends on the lifting range. The mean wrist joint velocity and acceleration values, in relation to the shoulder joint, increased. |

## Table 1 – Selected articles (continuation)

| Reference | Sample | Muscle Group | Task | Fatigue Measure | Equipment and Software | Conclusions |
|---|---|---|---|---|---|---|
| (Segala et al., 2011)<br><br>United States of America | 10 healthy right-handed subjects (6 male and 4 female) | Flexor Carpi Radialis, Extensor Carpi Radialis Longus, Biceps, Tríceps, Deltoids, Middle Trapezius, and Pectoralis Major. | Pushing a weight back and forth along a low friction horizontal track in time with a metronome until voluntary exhaustion. | sEMG; | Dynamometer; Reflective Markers; 8-camera Vicon-612 motion analysis system; Surface Electrodes; MatLab; Metronome; | Motion kinematic data can be used to track fatigue in local muscle groups. |
| (Gates et al., 2011)<br><br>United States of America | 10 subjects (4 women, 6 men) participated. Their mean (SD) age, weight, and height were 27.9 (2.2) year, 72.4 (18.2) kg, and 1.73 (0.10) m, respectively. | Trapezius, Pectoralis Major, Deltoids, Triceps, Biceps, Flexor Carpi Radialis, and Extensor Carpi Radialis Longus. | Repetitive task similar to sawing continuously until volitional exhaustion. Subjects performed the sawing task at shoulder (''High'') and sternum height (''Low''). | sEMG; | Dynamometer; Reflective Markers; 8 camera Vicon-612 motion analysis system; Borg Scale; Metronome; | Subjects altered their kinematic patterns significantly in response to muscle fatigue. They also exhibited increased kinematic variability of their movements post-fatigue. |
| (Gates et al., 2010)<br><br>United States of America | 20 healthy right-handed adults (9 female and 11 male); 25±2.2 years, 71.2±14.9 kg, and 1.71±0.10 m tall). | Pectoralis Major, Upper Trapezius, Deltoids, Biceps, Triceps, Flexor Carpi Radialis, and Extensor Carpi Radialis Longus Muscles. | Repetitive work task, similar to sawing, before and after performing each of two fatiguing tasks. The first fatigue task (LIFT) primarily fatigued the shoulder flexor muscles, while the second fatigue task (SAW) fatigued all of the muscles of the arm. | sEMG; | Reflective Markers; 8-camera Vicon-612 motion analysis system; Metronome; Borg Scale; | When performing multijoint redundant tasks, humans can compensate for muscle fatigue in ways that maintain task precision while increasing movement stability. |

The 15 articles included a total of 235 participants, more precisely 162 men (68,9%) and 73 women (31,1%).

The most studied muscle groups were the Anterior Deltoid (10 studies), Biceps Brachii (7 studies), Posterior Deltoids (6 studies), Triceps (5 studies) and Erector Spinae (4 studies).

The most performed task consisted in repetitive lifting of a box/load (5 studies), followed by a task similar to sawing (3 studies), push/pull weights (2 studies), arm flexion/extension (2 studies), biceps curl (2 studies) and automobile assembly task (1 study).

Analyzing the fatigue measurement methods, 9 studies used surface electromyography (sEMG), 2 studies used near-infrared spectroscopy (NIRS), 2 studies used a combination of sEMG and accelerometry, 1 study combined sEMG and NIRS. 1 study evaluated the effects of fatigue through torso kinematics/kinetics, linear/angular momentum and Lyapunov exponents.

Comparing the equipment used, only 2 studies used accelerometers (triaxial accelerometers), 10 used motion analysis system with cameras and 2 studies used magnetic motion capture system. In order to maintain a certain pace in the task performance, 5 studies used a metronome. The dynamometer was included in 6 studies.

The software used included Matlab in 3 studies, Visual-3D in 3 studies and LabView in 1 study.

A total of 7 studies applied the Borg scale (ratings of perceived exertion) or Borg CR-10 scale.

The articles had similar conclusions regarding movement variability, muscular adaptations and changes in movement strategies, due to fatigue.

The 2 studies that included accelerometry, (Brown et al., 2016; Dong et al., 2014), used sEMG as the fatigue measurement method and performed biceps curls. According to Brown et al. (2016), it is possible to distinguish between fatigued and non-fatigued sets of strength training based on acceleration data with a single parameter (calculated by a linear combination of duration and range of motion of each repetition). As a limitation, the fact that the volunteers could voluntarily slow down movement and manipulate kinematic data is mentioned. In the study performed by Dong et al. (2014), accelerometers were used to capture dynamic movements and impact simultaneously with the sEMG data measurements. They tracked localized muscular fatigue levels by constantly updating the measured parameters, considering the fatigue process as a dynamic process.

In the study performed by McDonald et al. (2016), they concluded that even tough kinematic and muscular changes allow workers to recover, they may not perceive existing fatigue, which may contribute to overuse injuries in the workplace. In order to maintain task performance, participants employed small compensations in several joint angles.

It was demonstrated in the study conducted by Mehta et al. (2015) that the behavioral changes observed when performing a prolonged repetitive asymmetric lifting activity likely increase the risk of back injury. When precise placement is required, larger sustained twisting postures and lateral bending moments on the spine occur.

The age factor was analyzed in Boocock et al. (2015) study, showing differences in lifting postures were found between the two age groups during the repetitive handling task. Lumbar mobility and dynamic range increased more in the younger group, which expose them to increased risk of injury. Peak lumbosacral, trunk, hip and knee flexion angles differed significantly between age groups over the duration of the task, as did lumbosacral and trunk angular velocities.

The effect of local and widespread fatigue was analyzed in the study conducted by Cowley et al. (2014). The conclusion was that after localized fatigue, subjects made shorter, slower movements, while after widespread fatigue subjects exerted less control over non-goal-relevant variability and did not change movement patterns. Although they altered their control strategies, they continued to achieve the timing goal after both fatigue tasks.

Physiological and biomechanical responses to prolonged repetitive asymmetric lifting activity was assessed by Mehta et al. (2014), showing that it leads to behavioral changes. Participants repetitively lifted the box in a stooped posture they bent more over time.

Work experienced was evaluated in Lee et al. (2014) study, concluding that novices decreased peak lumbar moments post-fatigue, while experienced workers increased.

The study conducted by Spyropoulosa et al. (2013) evaluated two different lifting ranges and concluded that the volunteers used the stoop posture and achieved a better blood flow to the upper limbs, which helped to recover and delay fatigue accumulation.

The effect of different heights was evaluated in Gates et al. (2011), showing that subjects fatigued more quickly when movements were performed at the high height, they altered their kinematic patterns and exhibited increased kinematic variability of their movements post-fatigue.

## 2.4 CONCLUSIONS

The 15 articles included in this systematic review demonstrated that muscle fatigue leads people to change their movement patterns and changing kinetic or kinematic components of the movement (like joint angles and velocities).

Nevertheless, only 2 studies included accelerometers, in a combination with sEMG. Studies using only accelerometers to assess fatigue were not found, showing that there is a future research possibility in using this methodology, combined with a motion analysis system. This way, by monitoring adaptations to muscle fatigue and evaluating kinetic and kinematic changes, muscle fatigue can be assessed.

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# PART 2

# 3 DEFINITION OF OBJECTIVES AND METHODOLOGY

## 3.1 Objectives

The main objectives of this study were:

a) Identification of muscle fatigue indicators that could be listed and checked in a real work environment.

b) Definition of a muscle fatigue assessment method based on movement measuring instruments, specifically accelerometers and motion analysis, in order to objectify a measurement technique susceptible of being applied in a controlled laboratory environment and possible to be replicated in a real work environment, which will encompass various synergistic effects.

To fulfill the dissertation goals, 2 articles were performed. The state of the art, presented in Chapter 2, consisted in a systematic review performed to summarize and analyze studies concerning muscle fatigue assessment using accelerometers and motion analysis. It contained general definitions of muscle fatigue and manual handling of loads and the databases used to complete the systematic review, according to PRISMA Statement. An explanation of the methodological procedures of the bibliographic research is presented, in order to guarantee the reproducibility and traceability of the same. This review helped to conceptualize the practical experiment, the equipment and the topics that should be addressed in the study. The equipment, procedure, results and discussion of the experimental study are presented in Chapter 4.

## 3.2 Methodology

The systematic review helped to conceptualize the experimental study that was later conducted. Starting with the volunteers, the selection had to comply with certain criteria, like the fact that they need to be healthy (without diseases or injuries), because it can impair their physical condition and ability to perform the exercise. Factors like smoking, alcohol consumption, sedentarism and eating habits had to be addressed with the help of a questionnaire.

According to **Figure 3**, repetitive hand and arm movements are the most prevalent posture-related risk and are almost equally reported by men and women (61% and 62%, respectively). This way, the same number of women and men were intended to be in study, to have a more comparable sample, but more than double females were included, more specifically 9 women and 4 men, because it was a convenience sample. All participants completed a questionnaire (**Annex 1**) in order to verify their eligibility to the experiment (all were eligible) and provided written consent (**Annex 2**).

The most performed task found in the systematic review consisted in repetitive lifting of a box/load and the pace was determined by a metronome. This way, the selected movement consisted in the repetitive lifting of a 2.5 kg load in a 0.5 m elevation and a metronome at 100 bpm was used. Although the articles included heavier loads than the selected, the intended objective was to have a gradual fatigue of the volunteers. If the load was heavier, most volunteers wouldn't be able to perform the exercise, not because they were tired, but simply because they wouldn't be able to lift the load consistently.

Although the initial idea of the study was to use accelerometers and motion analysis, the experiments only included motion analysis. A BioPlux Research device with force sensors and triaxial accelerometers was tested but inconsistent output data and calibration struggles made it impossible to use these accelerometers. To overcome this obstacle, Xsens products, namely accelerometers and motion tracking modules, were researched online. A 3D human kinematics system (MVN Biomech) and an inertial motion capture (Xsens MVN) were found, but all products were unavailable. Therefore, it was decided to only use motion analysis instead. The motion analysis software from Video4Coach, namely SkillCapture version 2.0.6 and SkillSpector Version 1.2.4., alongside two Logitech C920 HD Pro Webcams, were used.

With the defined methodology, the experimental study was conducted inside a climatic chamber (FITOCLIMA 25000EC20), which enabled the selection of specific climatic conditions.

The participants completed a questionnaire (**Annex 1**) in order to verify their eligibility to the experiment and provided written consent (**Annex 2**).

# 4 EXPERIMENTAL STUDY – MUSCLE FATIGUE ASSESSMENT IN MANUAL HANDLING OF LOADS USING MOTION ANALYSIS

# Muscle Fatigue Assessment in Manual Handling of Loads using Motion Analysis

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ABSTRACT: Muscle fatigue refers to the transient decrease in the capacity to perform physical actions and can cause productivity loss, human errors, unsafe actions, injuries and work related musculoskeletal disorders (WMSDs). A total of 13 participants repetitively lifted a 2.5 kg load at a total elevation of 0.5 m, until voluntary exhaustion or intensive pain. Several indicators of muscle fatigue were found, including increased forward bending, micro expressions, changing load support strategy, holding load closer to the chest during elevation and increase in eccentric movement speed. Volunteers that practiced sports regularly lasted longer in the experiment and it was found that smoking and sedentarism limited the exercise capacity of some subjects. Volunteers increased the wrists and elbows velocity during the experiment, especially on the left side of the body. It was verified that half of the volunteers had less fluid movement during lifting, with higher acceleration values in some parts and lower values in others, translating into more impulsive movements. It was concluded that to compensate muscle fatigue, people adapt their working strategy, changing movement patterns, recruiting different muscles and changing kinetic or kinematic components of the movement (like joint angles and velocities).

**Keywords:** Motion Analysis, Manual Handling of Loads, Movement Variability, Repetitive Movements, Biomechanics.

**Presentation Preference:** Oral

## 4.1 INTRODUCTION

According to Enoka et al. (2008), muscle fatigue refers to the transient decrease in the capacity to perform physical actions and the decrease in the maximal force or power (velocity of muscle contraction) that the involved muscles can produce. It can be categorized as one of the symptoms of blood occlusion, because limited blood flow delivers insufficient oxygen and nutrients, alongside the inadequate removal of metabolic waste products, causing lactate concentrations to rise (Oyewole, 2014).

Manual handling of loads consist in any of the following activities: lifting, holding, putting down, pushing, pulling, carrying or moving of a load. Fatigue accumulation can be extended by practicing proper work/rest time ratio and controlling the lifting variables (Halim et al., 2014).

A significant level of muscle fatigue can cause productivity loss, human errors, unsafe actions, injuries and work related musculoskeletal disorders (WMSDs) (Sluiter et al., 2003; Toole, 2005; Huang and Hinze, 2006; Hallowell, 2010).

During repetitive and fatiguing work, the musculoskeletal system adapts and uses momentary muscle substitution patterns, which result in more variable and less coordinated movements (Mehta et al., 2015).

A study of dynamic lifting conducted by Chen (1999), revealed that the lifting range differed significantly when participants felt fatigue in the upper limbs and that they used increasingly stooped and accelerated techniques at the beginning of the lift, followed by the stiffness of the arms at the end of the lift.

A recent review, performed by Srinivasan and Mathiassen (2012) concluded that motor variability is a relevant issue in an occupational context and that there is a great need for studies of motor variability. They suggest future research in creating methods to assess motor variability and study the relationship with occupational tasks and outcomes like fatigue and performance.

The main goals of this study were:

a) Identification of muscle fatigue indicators that could be listed and checked in a real work environment;

b) Definition of a muscle fatigue assessment method based on motion analysis, in order to objectify a measurement technique susceptible of being applied in a real work environment.

## 4.2 MATERIAL AND METHODS

### 4.2.1 Participant Selection

Participants must be healthy, because any diseases or injuries may influence muscle performance and lead to inconsistent findings. Variables like lifestyle, eating habits and medical history are important.

According to Jeukendrup (2014), caffeine has shown to improve endurance performance and is a common supplement used in endurance sports, being consumed in beverages due to its work-enhancing and alertness effects. He suggests that to optimize endurance exercise, people must have high carbohydrate consumption and adequate drinking (dehydration can compromise exercise performance). Carbohydrate and protein intake reduce the development of fatigue, according to Currel (2014).

Smoking and alcohol consumption also influence the results, alongside age and gender differences (Al-Mulla et al., 2011). According to Wüst et al. (2008) smokers have lower skeletal muscle fatigue resistance and the increased fatigability is due to the reduction in oxygen supply to the muscle. It was concluded by Bogdanis (2012) that sedentary lifestyle and/or cardiovascular and pulmonary diseases may limit exercise capacity and increase fatigability.

In order to analyze these variables, a questionnaire divided in 4 topics (personal data, lifestyle, eating habits and medical history) was created.

### 4.2.2 Sample Characteristics

A total of 13 participants were recruited, namely 4 men and 9 women. All volunteers had normal weight, except one of the males that was on the edge of overweight (due to higher muscle mass). Their characteristics are presented in **Table 1**. All participants provided informed written consent.

**Table 1** – Subjects Characteristics

| | Age | Height (m) | Weight (kg) | BMI (kg/m$^2$) |
|---|---|---|---|---|
| Males | 24 ± 0.8 | 1.83 ± 0.08 | 76.8 ± 7.3 | 22.9 ± 2.2 |
| Females | 24 ± 1.2 | 1.65 ± 0.05 | 62.7 ± 3.8 | 23.0 ± 1.6 |

### 4.2.3 Apparatus/Equipment

The experiment was conducted inside a climatic chamber (FITOCLIMA 25000EC20), which enabled the selection of specific climatic conditions.

A 2.5 kg load was used by the subjects. A table with a box on top dictated the height that volunteers needed to overcome with their arms. A metronome at 100 bpm established the pace that every subject should perform the exercise. The calibration object was a cubic structure with 50 cm edge.

The software used consisted in a motion analysis software available from Video4Coach, namely SkillCapture version 2.0.6 and SkillSpector Version 1.2.4. The first one was used to record the experiment, alongside two Logitech C920 HD Pro Webcams, each one placed in the left and right side of the person, at around 45 degrees. The recordings were then studied in SkillSpector.

A digitizing model and a calibration model were created. The digitizing model included a total of 12 points, namely two on the fingers, two on the wrists, two on the elbows, two on the shoulders, one on the neck and one on the top of the head. Segments were defined as an element going from one point to another. For example, the forearm was the segment between the wrist and elbow points. The calibration model included 8 points, each in every corner of the 50 cm edge cubic structure.

Volunteers had markers placed in strategic parts of the upper body, as shown in **Figure 1**, in order to improve the video analysis and creation of the body segments in the 3D model, as presented in **Figure 2**.

The 3D model was built by marking each reference point placed on the volunteer body in each frame (1 frame = 0.03 s) of the video. Since two cameras were used, this had to be done twice, one for each recorded video. Because of this limitation, only the differences between the first and last movements of lifting and lowering were studied, considering that the last movement before voluntary exhaustion is the most representative of muscle fatigue.

The average time for lifting and lowering of the load was 5 s. This means that to analyze just 5 seconds of the movement, 167 frames were studied in each camera. A total value of 668 frames, each one containing 12 marked points, was studied for each one of the 13 volunteers.

The body position was calculated using a DLT algorithm (Direct Linear Transformation) which was found based on the calibration object. This is the mathematical methods used to transform image data to real world coordinates.

**Figure 1** – Body Segments and markers

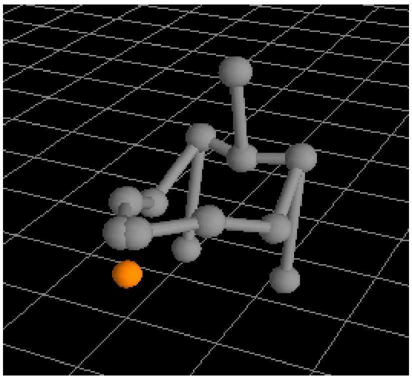

**Figure 2** – 3D model created in SkillSpector

### 4.2.4 Experimental Procedure

The study started with the completion of a short questionnaire that covered 4 topics, namely: personal data, lifestyle, eating habits and medical history. After completing the questionnaire and verifying that subjects were eligible for the study, the experiment was explained to the volunteers and informed consent was signed.

The experiment was conducted inside a climatic chamber, where specific conditions were set, namely 25 ± 2 ºC temperature and 49 ± 5 % relative humidity.

At the beginning of the study, a cubic calibration structure with 50 cm edge was placed where the volunteers would perform the exercise, as shown is **Figure 3**, with the 3 adopted axis that were used. This axis orientation was selected because the program calibration tutorial adopted this orientation.

The volunteers repetitively lifted a 2.5 kg load (dumbbell disk) from a 0.72 m height to 1.22 m, meaning a total elevation of 0.5 m, until voluntary exhaustion or intensive pain, that is, until they no longer could perform the task. While performing the exercise, two video cameras recorded the movements performed and these images were subsequently analyzed. A metronome (100 bpm) marked the pace that volunteers needed to perform the lifting and lowering movements of the load so that all volunteers performed the task under equal conditions. **Figure 4** shows the experiment layout and **Figure 5** represents the lifting and lowering movement executed by the participants.

The experiments were conducted in the morning between 8 a.m. and 12 p.m., in order to have rested volunteers. Otherwise, muscle condition would be influenced by daily activities.

Ratings of perceived exertion (RPE) were gathered using the modified Borg scale. Subjects rated their level of fatigue on a scale from 0 (none at all) to 10 (maximal exertion) at the end of the experiment. Subjects were also asked about the physical symptoms they experienced throughout the experiment and these were noted down.

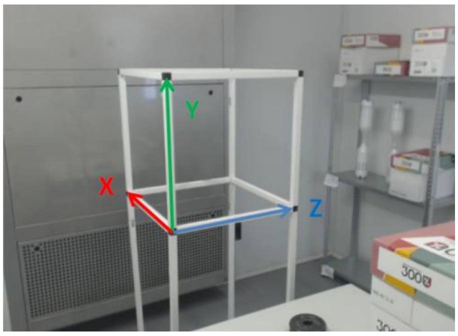


**Figure 3** - Calibration Object

**Figure 4** – Experiment layout

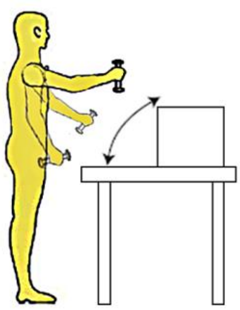

**Figure 5** – Lifting and lowering movement

### 4.2.5 Statistical analysis

The gathered data stored in SkillSpector was exported to Microsoft Excel in order to perform statistic tests. The statistical analysis add-in XLSTAT was used because it offers a wide variety of functions to enhance the analytical capabilities of Excel.

Since the original data was calculated relative to the calibration structure, the initial frame was used as a reference and all the following frames were calculated relative to that initial frame. That way, both sides of the body could be compared equally and easier. Otherwise, the Z values (horizontal length) of the left side of the body were always higher than the right side, because it was further to the calibration structure origin. The results from the X-Axis had to be converted from negative values to positive values, because the positive direction was opposite to the volunteer's orientation.

Normality tests were performed in order to determine the normality of the data, namely Shapiro-Wilk, Anderson-Darling, Lillefors and Jarque-Bera tests. Outliers were detected with Grubbs test.

Student's paired t-test compared the means of two series of measurements performed on the same statistical units, namely the information of the first and final movements.

Box-and-whisker plots were used to present the results. These graphics contain crosses (means), the central horizontal bars (medians) and the lower and upper limits of the box (first and third quartiles, respectively). Points above or below the whiskers upper and lower bounds may be considered as outliers.

Tests were carried out to verify the normality assumptions based on skewness and kurtosis, considering the criteria proposed by George and Mallery (2010) of skewness and kurtosis values within ± 2.

## 4.3 RESULTS AND DISCUSSION

### A. Questionnaire results

The questionnaire covered 4 topics, namely: personal data, lifestyle, eating habits and medical history. **Table 2** sums the main results of the questionnaire.

In terms of lifestyle, 9 in 13 participants played sports regularly (3 out of 4 males and 6 out of 9 females), only 1 female smoked and 4 in 13 (2 out of 4 males and 2 out of 9 females) admitted they had a sedentary lifestyle. In average, males sleep 8 ± 0 h/day while females sleep 7.2 ± 0.4 h/day.

**Table 2** – Questionnaire results

| Name | Plays Sports | Smokes | Sedentary Lifestyle | Coffe Regularly |
|---|---|---|---|---|
| Male 1 | **Yes** | No | No | **Yes** |
| Male 2 | **Yes** | No | **Yes** | **Yes** |
| Male 3 | No | No | **Yes** | **Yes** |
| Male 4 | **Yes** | No | No | **Yes** |
| Female 1 | No | **Yes** | **Yes** | **Yes** |
| Female 2 | No | No | **Yes** | No |
| Female 3 | **Yes** | No | No | **Yes** |
| Female 4 | **Yes** | No | No | No |
| Female 5 | No | No | No | **Yes** |
| Female 6 | **Yes** | No | No | **Yes** |
| Female 7 | **Yes** | No | No | No |
| Female 8 | **Yes** | No | No | **Yes** |
| Female 9 | **Yes** | No | No | **Yes** |

In terms of eating habits, males and females had in average 5 ± 1 meals/day. A total of 10 people drink coffee regularly (only 3 females don't drink). None of the participants consume alcoholic drinks regularly or was taking a diet or was vegetarian.

The medical history of the volunteers showed that none of them was taking medication and none was stressed at the time of the experiment. Some diagnosed medical conditions were the allergy to mites (2 males and 1 female), asthma (female 2 and 5) and tendonitis on the right wrist (female 4).

Analyzing the data, there is a slight tendency for people that practice sports to hold on longer in the experiment. Female 1 and 2 only kept doing the experiment for 7 and 10 minutes (see **Figure 6**) and both of them didn't practice sports regularly. In the males, male 3 was the only one that didn't practice it regularly, but hold for 45 minutes (more 11 minutes than male 2).

The only smoker was female 1, the one that only did the experiment for 7 minutes, which shows that smoking may harm physical condition. In terms of sedentarism, female 1 and 2 are the only females that admit they have a sedentary life, showing that the lack of exercise might have an influence on the results. The asthmatic condition of female 2 probably contributed for such a low time.

The asthmatic condition of female 2 probably contributed for such a low time. On males, the results are not conclusive, since male 2 and 3 considered themselves sedentary and hold more than male 1. On the other side, male 4, the person that stayed in the experiment for 1 h, didn't consider to have a sedentary life.

Most volunteers consumed coffee regularly, only female 2, 4 and 7 didn't. Since they consume it regularly, their body already adapted to a certain daily dose and side effects don't appear. Alterations appear when they consume a higher quantity, or don't consume any.

Female 1 combined the negative effects of smoking with sedentary life, which might explain her lower performance. She was also the person that consumed more coffees per day (4 coffees), the double than other volunteers. According to Treloar et al. (2014), smoking increases caffeine metabolism, which means that smokers need to consume more caffeine to achieve the desired effects.

### B. Posture and behavioral changes recorded on camera and symptoms described by the volunteers

According to literature, higher movement variability occurs with the development of muscle fatigue (Brown et al., 2016). Muscular and kinematic adaptations occur to reduce the load on the fatigued muscles (McDonald et al., 2016). Other studies concluded that fatigue induced changes in movement strategies (Lee et al., 2014) and subjects altered their kinematic patterns significantly in response to muscle fatigue (Gates et al., 2011).

In order to confirm if any of these conclusions were also observed in the experiment, the recordings were analyzed.

Before starting executing the exercise, volunteers performed 4-5 repetitions to understand the intended movement. Volunteers displayed similar behavior, with relaxed body language and well coordinated movements.

Since no warm up exercise was performed, the first movements of the experiment were used by the volunteers to warm up the body, increase heart rate, get the blood flowing to the muscles, tendons and ligaments and mentally preparing for the workout. It was noticed that after some repetitions, the volunteers demonstrated a better performance, which might indicate the importance of a good warm up before exercising. It also demonstrates that people need to adapt to the situation before reaching max potential and achieve high work efficiency, which will then decrease over time, as muscle fatigue increases.

As the experiment went on, the first noticeable changes were micro expressions (involuntary facial expressions), such as biting or narrowing lips during elevation and eyebrows down and together. These were signs that volunteers were starting to feel uncomfortable. An increase in breathing pattern also occurred.

Volunteers started to change the way they executed the exercise by lifting and holding the load in different ways than the initial. The load was meant to be lifted horizontally relative to the table. Some volunteers started to rotate the disk during the elevation and making it vertical to the ground at maximum elevation. Others opted to sustain it from below, with the hands together and palms facing up. The ones that kept the hands in the intended position started to tighten and release the fingers on the load, trying to get better grip and also enable some rest in each hand.

The movements started to be less fluid and while lowering the load, subjects increased eccentric movement speed, using gravity to help them lower the load.

At the start of the lifting and when they inverted lifting to lowering, subjects demonstrated increasing stooped position, as well as slight head bending forward. When inverting lifting to lowering, subjects struggled to maintain their position.

Another aspect noticed was that people started bending their neck sideways, to relief tension on the trapezius muscle and on the shoulders. They also rotated their shoulder from time to time.

Due to the fact that volunteers were standing still, they started decreasing their body stability and started balancing more. They started to hold their body on one leg and then changing to the other. The fact that some volunteers felt discomfort in the legs (numb legs), although the experiment only directly fatigued upper limbs, shows that there might be correlation between upper and lower body. By standing still and frequently keeping the arms horizontally at shoulder level, this corresponds to static muscle work, which means that the blood requirement was higher than the supply. This follows the conclusions made by Oyewole (2014), because limited blood flow delivers insufficient oxygen and nutrients. This means that when studying muscle fatigue, the whole body should be assessed together.

Subjects started noticing they were adopting a stooped position and started stretching their body and spine from time to time, in order to correct their posture and relief tension in their lower back.

In the final stages of the experiment, the movement started to be performed by lifting the load up to the chest and then moving it forward, instead of the gradual elevation and move away from the body. This strategy was used to compensate muscle fatigue and because lifting a load closer to the body is easier to perform.

As the experiment went on, some struggled to follow the metronome rhythm and started executing the movement in a very fast pattern, while others performed it slowly. This might indicate that people started losing focus.

Another important aspect is the fact that there were no external influences/incentives contributing to the subject’s activity. Some volunteers expressed that they would probably do better if they were listening to music or watching a video. The recordings show that volunteers started looking for something inside the chamber to focus, looking up and down, to both sides, in order to distract themselves. Others suggested that more than one person should do the experiment at the same time, so they could talk and distract themselves. This might mean the psychologic component is also important, making mental fatigue influence physical performance. A recent systematic review conducted by Van Cutsem et al. (2017) assessed the effects of mental fatigue on physical performance. It concluded that mental fatigue impairs endurance performance and is mediated by a higher than normal perception of effort.

Summing up, the posture and behavioral alterations observed in the recordings included:

a) Micro expressions (involuntary facial expressions) including biting or narrowing lips during elevation, eyebrows down and together;
b) Increased breathing pattern;
c) Changing load support strategy (hand and wrist posture);
d) Tightening and releasing fingers on the load, trying to get better grip;
e) Increase in eccentric movement speed, following the conclusion of Brown et al. (2016).
f) Increased forward bending, also described by Mehta et al. (2014);
g) Head slightly bending forward;
h) Neck bending sideways;
i) Decrease in body stability;
j) Changing support leg (some volunteers started to feel numb legs);
k) Stretching body and spine;
l) Holding load closer to the chest during elevation in the final stages of the experiment, resulting in a less fluid movement. This shows volunteers adapted to compensate fatigued muscles, which was also concluded by McDonald et al. (2016), Lee et al. (2014) and Gates et al. (2011);
m) Increased difficulty to follow metronome rhythm;

Symptoms described by the volunteers included discomfort in the wrists, brachioradialis, biceps brachii, triceps brachii, deltoids (anterior, medial and posterior), erector spinae muscles and gastrocnemius muscle.

### C. Total execution time, Borg Scale, initial and final movements time

The total execution time, Borg Scale and initial and final movements time are presented in **Table 3**. The total time in the experiment of each participant, both males (M) and females (F), is presented in **Figure 6**, while **Figure 7** presents the Borg Scale values, from 0 (none at all) to 10 (maximal exertion).

**Table 3** – Total time, Borg Scale, initial and final movements time

| | $t_{total}$ (s) | Borg Scale | $t_i$ (s) | $t_f$ (s) |
|---|---|---|---|---|
| Males | 40.5 ± 15.8 | 4.3 ± 0.9 | 4.8 ± 0.4 | 5.0 ± 0.1 |
| Females | 18.3 ± 9.9 | 5.3 ± 1.9 | 5.0 ± 0.3 | 4.6 ± 0.7 |

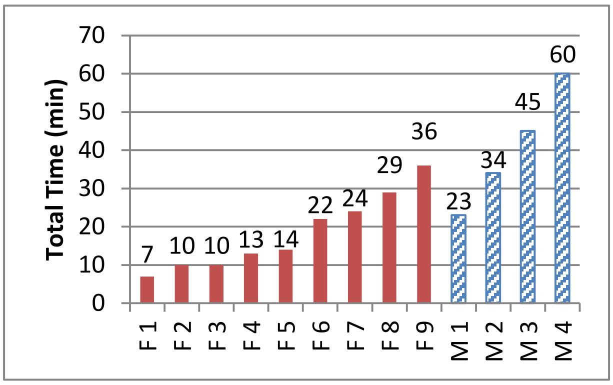


**Figure 6** – Total time in the experiment

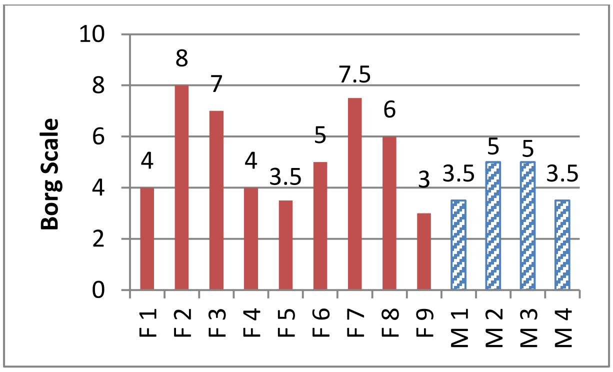


**Figure 7** – Borg Scale values

Analyzing **Figure 6**, it seems that the males could handle more time performing the experiment. Male 3 and 4 had the biggest times, with 45 and 60 minutes respectively. The 3rd biggest time belongs to female 9, with 36 minutes, followed closely by male 2 with 34 minutes. Female 1 had the lowest time, with only 7 minutes of exercise.

Subjects rated their level of fatigue on a scale from 0 (none at all) to 10 (maximal exertion) and the scores are presented in **Figure 7**. The highest scores were given by female 2, 3 and 7. Female 2 and 3 did the same time (10 minutes) and gave similar Borg scale results (8 and 7 respectively), corresponding to a really hard exercise. Female 7 gave a similar score and did the experiment for 24 minutes. Female 9 gave the lowest score and was the female that did the experiment for a longer time. On the other side, female 1 only gave a value of 4, half of female 2, which shows that it might not be self-aware of her fatigue level. In a work environment, this can lead to excessive effort and cause injuries. Male 1 and 4 gave the same score, although male 4 lasted three times more in the exercise.

Due to the fact that the metronome dictated the rhythm, the times were very similar in each person, as presented in **Table 3**. The volunteers struggled more in the final part of the experiment to match the metronome rhythm. Due to almost constant execution time (around 5 seconds) the number of repetitions followed a linear tendency.

## D. Statistical Results

The statistical results, namely the Student's paired t-test, of the wrists, elbows and shoulders are presented in **Figure 8**, **Figure 9** and **Figure 10**, respectively. The dashed line boxes mark the lowest p-values obtained in terms of position, velocity and acceleration.

Four normality tests were performed in order to determine the normality of the data, namely Shapiro-Wilk, Anderson-Darling, Lillefors and Jarque-Bera tests.

Student's paired t-test compared the means of two series of measurements performed on the same statistical units.

## E. Wrists

**Figure 8** analysis can be divided in the following parts:

### 1) Wrists range (position) on X axis (Range of motion):

In order to test the hypothesis of forward bending increase and assess if participants lifted the load in a stooped posture that they bent more over time, as concluded by Mehta et al. (2014), the highest position values in the X axis were analyzed. Grubbs test identified outliers and female 3 was removed in order to have a normal distribution.

The normality tests showed that the results followed a normal distribution, because the p-values (bilateral) were greater than the significance level (alpha = 0.05).

In the Student's paired t-test results, as shown in **Figure 8**, the calculated p-value (bilateral) for both wrists was greater than the significance level alpha = 0.05 (R Wrist = 0.47 and L Wrist = 0.95), meaning that the initial hypothesis “The difference between the means is equal to 0” shouldn’t be rejected. This means that no significant differences were observed in the wrist range mean in the X axis.

The results demonstrated that the individuals increased their wrist range on the X-Axis. Overall, the right wrist displayed more changes in terms of interquartile range, which translated to a much more concise pattern of the volunteers, probably because only 1 person was left handed. Right handed people might command that hand with more intensity and support more weight, in order to get higher stability, while their left hand is used for balance.

The downside of these results is that each person had different arm lengths, meaning that some subjects may have higher range on X axis because they had longer arms and not because they bended more over time.

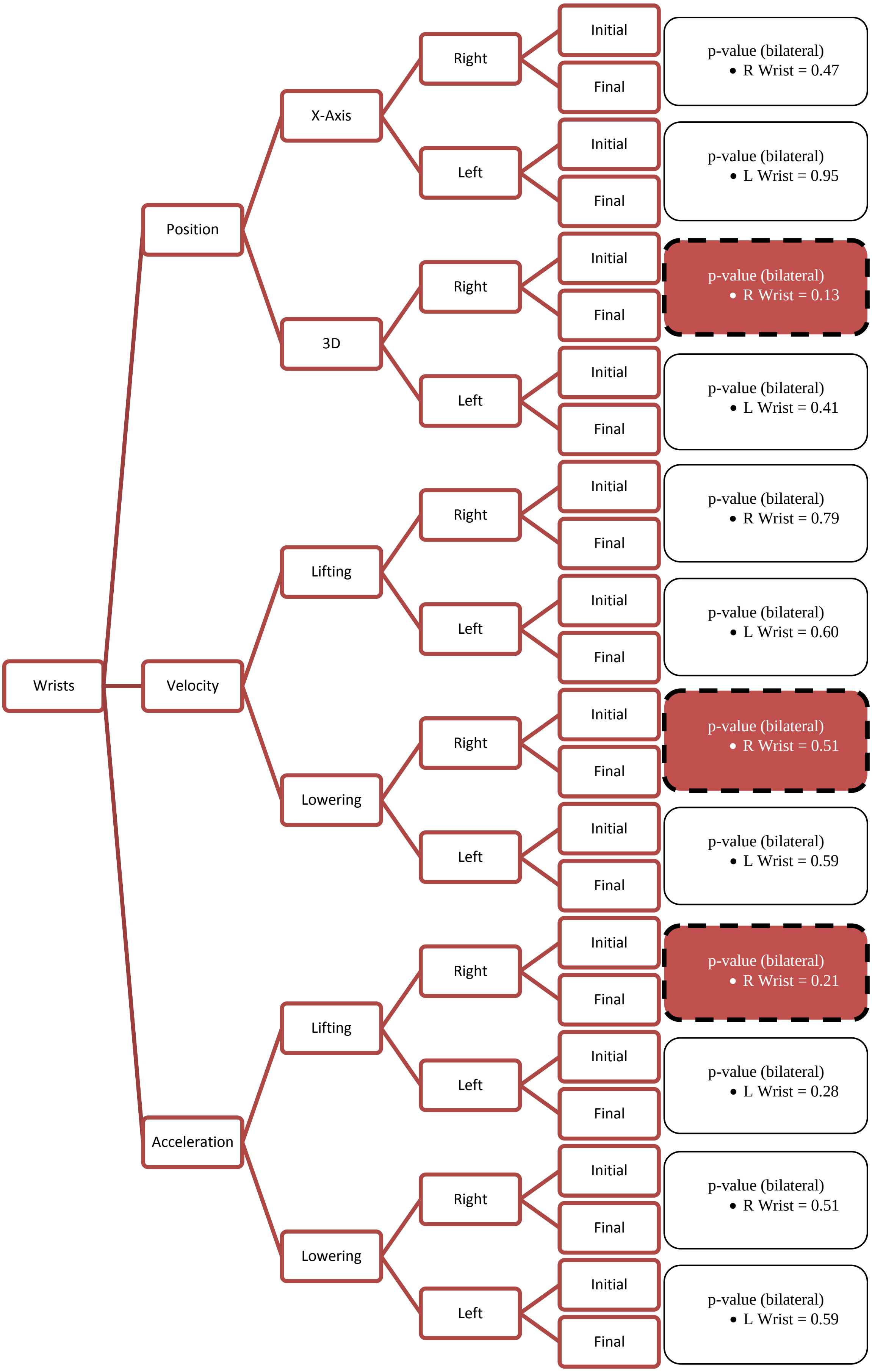


**Figure 8** – Wrists Student's paired t-test results

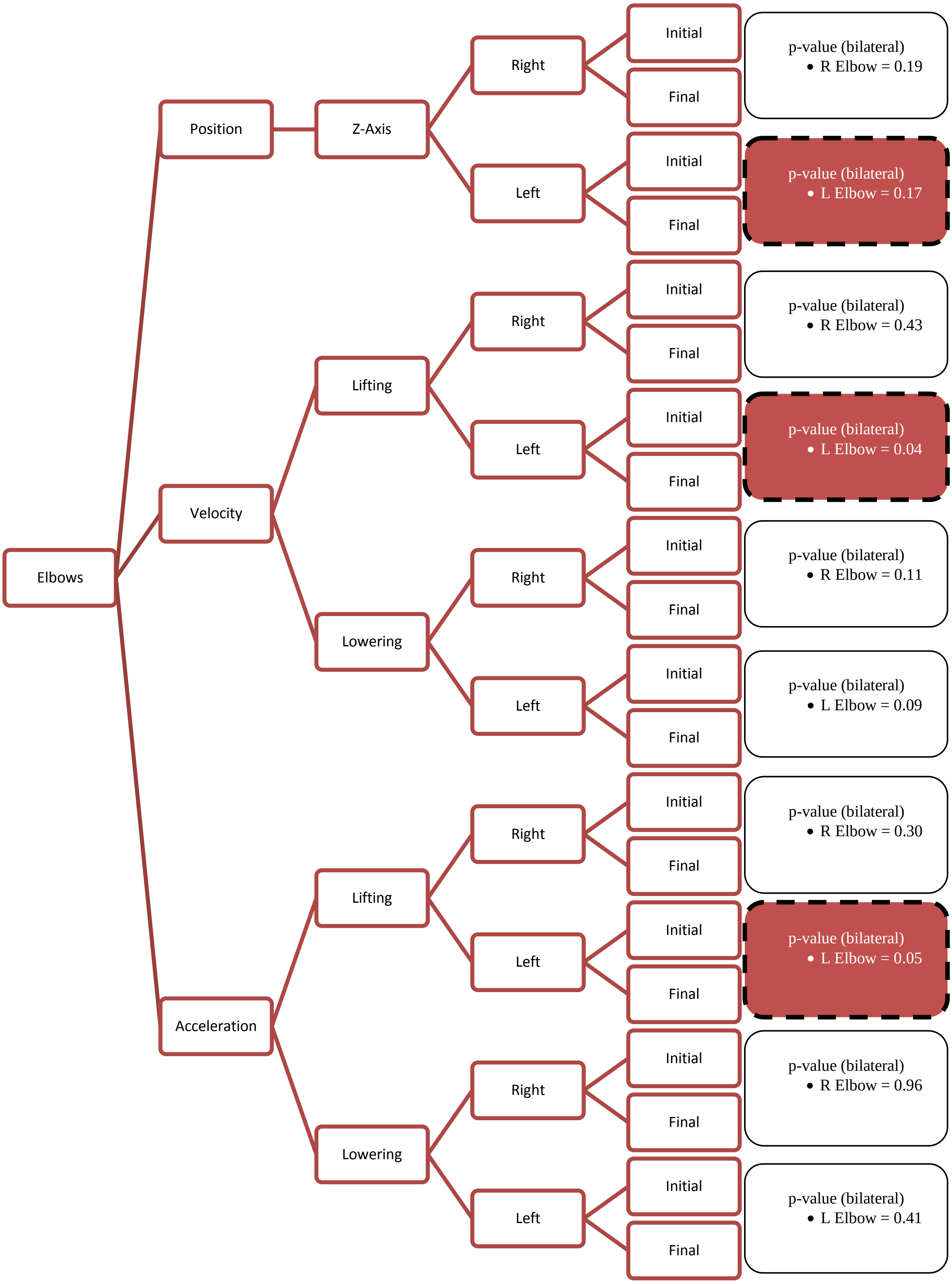


**Figure 9** – Elbows Student's paired t-test results

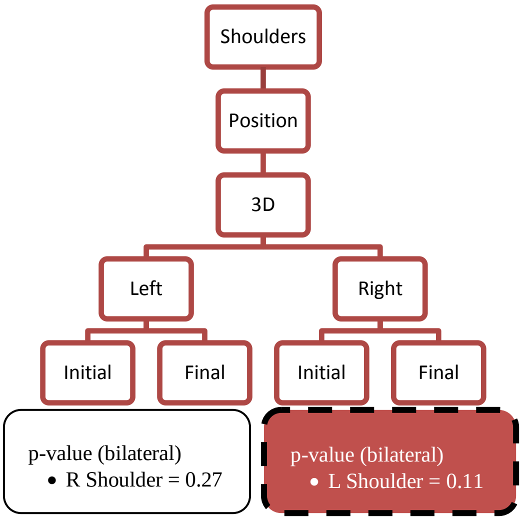


**Figure 10** – Shoulders Student's paired t-test results

### 2) Wrists 3D Position

The combination of the results in the 3 axis made it possible to obtain the 3D position values. Grubbs test identified outliers and female 3 was removed in order to have a normal distribution. The highest 3D position values were analyzed because they occurred at the inversion point between lifting and lowering. The data followed a normal distribution.

Analyzing the p-values, no significant differences were observed in the wrist 3D position means before and after. The right wrist displayed more changes (lower p-value).

### 3) Wrists 3D Velocity

In order to compare the lifting and lowering stages, the velocity analysis was divided in two sections. In both stages, the data analyzed was the highest velocity value verified.

Starting with the lifting stage, male 2 was removed in order to have a normal distribution. The calculated p-value (bilateral) for both wrists was greater than the significance level alpha = 0.05 (R Wrist = 0.79 and L Wrist = 0.60), meaning that no significant differences were observed in the wrist 3D velocity means before and after.

The left wrist had a more prominent alteration when compared to the right wrist (lower p-value). This translates into a higher variability of velocity values on the non-dominant hand. The reason might be that the right wrist is more controlled and needs to be more stable and regular in the movements. Nonetheless, the results showed that both wrists increased their velocity, although some people decreased it.

On the lowering stage, female 7 was removed in order to have a normal distribution. No significant differences were observed in the wrist 3D velocity mean before and after, but the right wrist had lower p-value.

The results showed that the lowering velocity increased. This follows the conclusions made by Brown et al. (2016) that stated that there could be an increase in eccentric movement speed since the muscle cannot resist the gravitational force.

### 4) Wrist 3D Acceleration

Following the same line of thinking, in order to compare the lifting and lowering stages, the acceleration analysis was divided in two sections. In both stages, the highest acceleration variation verified was studied, since the objective was to analyze how each person varied its own acceleration and not the actual acceleration values. Because of the high noise level in the acceleration results, a moving average was applied in order to decrease it.

In the lifting stage, male 1 was removed in order to have a normal distribution. Lilliefors test result for the left wrist initial value was below 0.05.

The p-value (bilateral) for both wrists was greater than the significance level alpha = 0.05 (R Wrist = 0.21 and L Wrist = 0.28), meaning that no significant differences were observed in the wrist 3D acceleration mean before and after. The right wrist demonstrated higher differences due to a lower p-value.

**Figure 11** shows differences in the right and left wrists, in the initial (I) and final (F) movements. In the right wrist the first quartile and the median decreased, while the mean and third quartile increased. On the other side, the left wrist only had the same pattern with the first quartile, since it increased the median, and decreased the mean and third quartile.

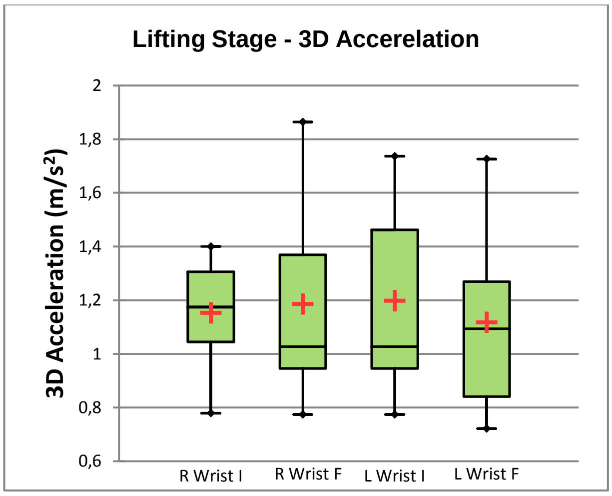


**Figure 11** – Wrists lifting 3D acceleration variation

The median on the right wrist final movement was below the first quartile value on the initial movement. A deeper analysis shows that in the right wrist final movement, 6 volunteers (50%) had between 0.8 to 1 $m/s^2$ difference between the maximum and minimum acceleration, while other 3 had from 1 to 1.4 $m/s^2$ difference and another 3 from 1.4 to 1.9 $m/s^2$. This means that half of the volunteers had lower acceleration variability in the final movement, with only maximum and minimum accelerations differing around 1 $m/s^2$, while the other half increased that difference. The half that increased had less fluid movement, with higher acceleration values in some parts and lower values in others.

In the lowering stage, Grubbs test identified female 7 as an outlier and it was removed in order to have a normal distribution. No significant differences were observed in the wrist 3D acceleration means before and after.

The variation in acceleration values increased on both wrists. This complements the conclusion of the velocity results where volunteers had a higher eccentric movement speed. Comparing the values, the mean value in the lifting stage was 1.16 $m/s^2$ and 1.21 $m/s^2$ in the lowering stage, meaning that the lowering stage had higher variation, since the volunteers would drop the load with the help of gravity, and not lower it carefully and in a sustained way.

## F. Elbows

**Figure 9** analysis can be divided in the following parts:

### 1) Elbows Z-Axis Range

One hypothesis that needed testing was the possibility that volunteers opened more the arms as the experiment went on, that is, they would increase the elbows movement in the Z-Axis. All the 13 volunteers were included. The results followed a normal distribution.

No significant differences were observed in the elbow Z-Axis means before and after.

The results showed that volunteers didn't open more the arms, but the other way around, they closed the elbows and hold them near the body, in order to increase stability and hold the load better.

### 2) Elbows 3D Velocity

In order to compare the lifting and lowering stages, the same strategy used for the wrists was applied, that is, the velocity analysis was divided in lifting and lowering.

In the lifting stage all subjects were included and a normal distribution was verified.

The p-value (bilateral) for the right elbow was greater than the significance level alpha = 0.05 but not the left elbow (R Elbow = 0.43 and L Elbow = 0.04), meaning that in the left elbow there was a significant difference in the 3D velocity mean before and after.

Observing **Figure 12**, that difference is noticeable. Comparing both elbows, they increased interquartile range, third quartile and range between maximum and minimum. While the right elbow almost didn't change median, on the left elbow it rose from 0.44 to 0.52 m/s. The results indicate that volunteers performed the lifting with higher velocity in the final movement of the experiment, especially on the left elbow. The same conclusion was made with the wrists, also with more evidence on the left side. This means that both left wrist and elbow had higher differences from beginning to end.

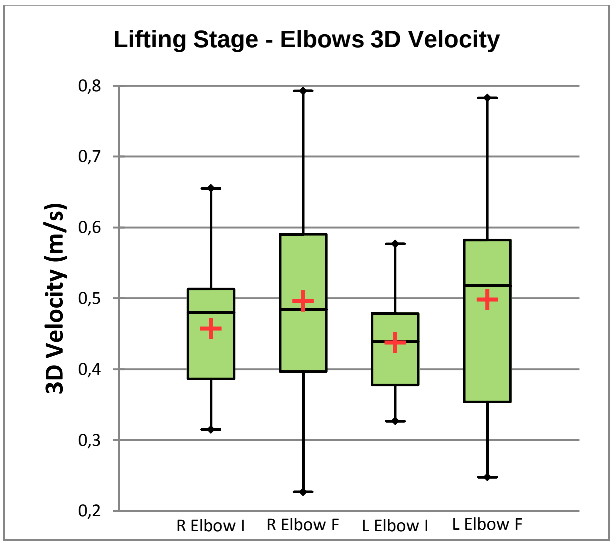


**Figure 12** – Elbows Lifting 3D Velocity

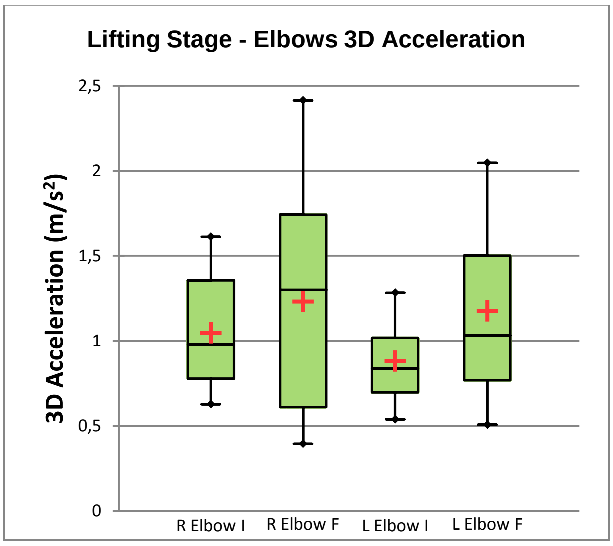


**Figure 13** – Elbows Lifting 3D Acceleration

In the lowering stage female 7 was removed in order to obtain a normal distribution. No significant differences were observed in the elbow velocity mean values.

The results demonstrated that the lowering movement was performed with higher velocity, following the same idea of the wrists and the conclusions made by Brown et al. (2016).

#### 2) Elbows 3D Acceleration

In order to compare the lifting and lowering stages, the acceleration analysis was divided in 2 sections. In the lifting stage, male 1 was removed in order to have a normal distribution.

Analyzing the p-value (bilateral) for both elbows, the left elbow had the alpha value, meaning that the differences were significant.

Observing **Figure 13**, both elbows increased the mean, median, third quartile, interquartile range and maximum value. This means that in the last movement, the difference between minimum and maximum acceleration values increased, translating into more impulsive movement.

### G. Shoulders 3D Position

Another way to analyze if the volunteers adopted a stooped position is through the shoulders 3D position. Grubbs test identified female 7 as an outlier and she was removed.

As shown in **Figure 10**, the p-value (bilateral) for both shoulders were greater than the significance level alpha = 0.05 (R Shoulder = 0.27 and L Shoulder = 0.11), meaning no significant differences were observed in the shoulders position mean values.

The results showed an increase in 3D position values and it was mostly contributed by an increase in the X and Y axis values, which correspond to a stooped position, both at the beginning/end of the movement and at the maximum arm extension in the sagittal plane.

## 4.4 CONCLUSIONS

This study intended to identify muscle fatigue indicators that could be listed and checked in a real work environment and define a muscle fatigue assessment method based on motion analysis.

The questionnaires results showed that there is a slight tendency for people that practice sports to have more endurance. On the other side, the lack of exercise and smoking might harm physical condition.

In order to compensate muscle fatigue, people adapted their working strategy and exhibited several muscle fatigue indicators. Males could handle more time performing the experiment.

The statistical analysis showed that individuals increased their range on the X axis (increased forward bending), both wrists increased their velocity in the lifting and lowering stage. In terms of acceleration, half the participants had less fluid movement during lifting, with higher acceleration values in some parts and lower values in others. Relatively to the elbows, subjects closed the elbows and hold them near the body, in order to increase stability and hold the load better. Volunteers performed the lifting with higher velocity in the final movement of the experiment, especially on the left elbow. Both left wrist and elbow had higher differences from beginning to end, than the right side.

### Strengths of the methodology

This methodology is a new approach that allows the assessment of common symptoms and behaviors that people demonstrate when starting to feel muscle fatigue, which could be listed and used as indicators in the work environment.

Motion analysis can be combined with accelerometry in order to assess muscle fatigue, by noticing changes in accelerations and movement patterns, as well as angles between wrist, shoulder and elbow.

A specific checklist could be created for each type of work, by performing a pilot test with some volunteers and analyzing the recordings. That way, a list of indicators could be used in the future, to enable a quick assessment of the worker's physical condition. If some of the symptoms were observed, safety and hygiene engineers could go talk to the workers and ask them how they are feeling and what problems they are facing, because they are the ones performing the task and have the knowledge of what could be improved and what they are really feeling.

### Limitations of the methodology

The main limitation of this study is the fact that only the first and last movements of lifting and lowering were studied, because the video analysis was made manually by marking each reference point placed on the volunteer body in each frame of the video (1 frame = 0.03 s), which made it impossible to assess the entire recordings. The last movement could be influenced by the volunteer and negatively affect the results. The gradual development of muscle fatigue and registered symptoms were only described and not quantified.

The ideal solution would be the continuous analysis of the recordings, with automatic live results, that allowed a fast assessment of the situation.

The analyzed sample of 13 people is not the ideal sample size to generalize the results and future work should include a larger and representative sample.

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# 5 FINAL REMARKS AND FUTURE WORK

The current research provides an increased understanding of muscle fatigue development, the symptoms and indicators that can help identifying it. Overall, the findings from this research contribute to the body of knowledge in the field of ergonomics.

A significant level of muscle fatigue can cause productivity loss, human errors, unsafe actions, injuries and Work Related Musculoskeletal Disorders (WMSDs) that are one of the most common work-related complaints and affect millions of workers. Several causes have been identified such as repetitive movements, heavy lifting, frequent bending and twisting and insufficient recovery time.

A review of existing studies concerning muscle fatigue assessment using accelerometers and motion analysis was conducted. From the 15 articles included, only 2 studies included accelerometers, in a combination with sEMG. No studies using only accelerometers to assess fatigue were found, showing that there is a future research possibility in using this methodology, combined with a motion analysis system.

In the experimental study, several indicators of muscle fatigue were found, including increased forward bending, micro expressions, changing load support strategy, holding load closer to the chest during elevation and increase in eccentric movement speed. When comparing the results with the questionnaires, it was concluded that volunteers that practiced sports lasted longer in the experiment and it was found that smoking and sedentarism limited the exercise capacity of some subjects. This shows that companies should encourage their employees to have good health habits, such as regular physical activity, adequate sleep, good eating habits (high carbohydrate consumption and adequate drinking) in order to reduce the development of fatigue.

Warming up and stretching are very important since they increase heart rate, get the blood flowing to the muscles, tendons and ligaments, prevent problems such as muscle tightness and mentally prepare people for the work. These practices should be encouraged before exercising or performing manual handling of loads.

It was concluded that to compensate muscle fatigue, people adapt their working strategy, changing movement patterns, recruiting different muscles and changing kinetic or kinematic components of the movement. The results show that volunteers increased the wrists and elbows velocity during the experiment. Volunteers had less fluid movement during lifting, with higher acceleration values in some parts and lower values in others, translating into more impulsive movements.

This methodology can complement the results of observational techniques for assessing postural load, namely, OWAS (Ovako Working Posture Analyzing System), RULA (Rapid Upper Limb Assessment) and REBA (Rapid Entire Body Assessment). These techniques present some limitations, such as the fact that the person analyzing the workers has to understand the jobs task and select the most difficult postures that are sustained for a longer time and have higher force load. This means that the evaluation is static and subjective and is not made throughout the workers day, in touch with him and with real-time data analysis. These tools are used as verification and correction techniques, instead of monitoring.

Future research should create methods to assess motor variability and study the relationship between occupational tasks and outcomes like fatigue and performance.

In future studies, the experiment should be performed with different loads, elevation heights, and distance to box/shelf, in order to assess the effect of each variable on the muscle fatigue development. A heavier load could lead to faster fatigue development and decrease the total experiment time, but on the other side it shouldn't be heavy because the intention is to have a gradual fatigue development. The height could be tested for above head elevations, to see if other symptoms appear on lower limbs, since some volunteers noticed a discomfort on the legs on this experiment. A closer box/shelf is to make sure that the different arm length of volunteers doesn't affect the results.

Since all the participants had almost the same age, around 24 years, the influence of age could not be assessed. A future work comparing younger and older people would help determine if age influences the behavior of the participants.

The dominant hand or leg used by the volunteer should be specially focused, since it is mostly used and usually the one that supports more weight and it is subject to more effort, although the results show that the non-dominant side presents higher alterations.

Different movements can be analyzed, with different positions being assessed, including upper and lower body at the same time, if possible. The wrists, elbows, shoulders, hip, knees and ankles are the main joints that should be assessed.

In terms of software and equipment, a combination of accelerometers, motion analysis system and force sensors should be created, to assess with live results the alterations in body movements of workers. The equipment should collect data related to a 3D position, velocity, acceleration, joint angles and applied force. When a determined deviation occurs, a sound signal could inform the worker that they need to stop and change to another work position, to allow some rest.

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# ANNEX 1 - QUESTIONNAIRE

## Mestrado em Engenharia de Segurança e Higiene Ocupacionais

**Fábio Gabriel Pereira Bernardo**

**2016/2017**

No âmbito da Dissertação de Mestrado em Engenharia de Segurança e Higiene Ocupacionais (MESHO), solicita-se o preenchimento do seguinte questionário.

| **1. Detalhes Pessoais** | |
|---|---|
| Nome: | |
| Idade: | Sexo: ☐ Masculino ☐ Feminino |
| Profissão: | |
| Altura (m): | Peso (kg): |

| **2. Estilo de Vida** |
|---|
| 2.1) Pratica algum tipo de desporto/atividade física? ☐ Sim ☐ Não |
| Se sim, mencione: Qual? Desde quando? Com que frequência? |
| 2.2) Nas últimas 24h realizou alguma atividade que exigiu maior esforço físico? ☐ Sim ☐ Não |
| Se sim, qual? |
| 2.3) É fumador? ☐ Sim ☐ Não |
| Se sim, mencione: Desde quando? Quantos cigarros/dia? |
| 2.4) Quantas horas de repouso faz normalmente? ☐ Menos de 8h ☐ 8h ☐ Mais de 8h |
| 2.5) Considera ter um estilo de vida sedentário? ☐ Sim ☐ Não |

| 3. Hábitos Alimentares |
| --- |
| 3.1) Quantas refeições faz por dia? ☐ 3 ☐ 4 ☐ 5 ☐ 6 |
| 3.2) Consome café regularmente? ☐ Sim ☐ Não |
| Se sim, mencione: Quantos cafés/dia? Quantos nas últimas 24h? |
| 3.3) Consome bebidas alcoólicas regularmente?) ☐ Sim ☐ Não |
| Se sim, mencione: Que tipo de bebida? Quantidade nas últimas 24h? |
| 3.3) Que tipo de bebida consome com maior frequência? ☐ Água ☐ Cerveja ☐ Vinho ☐ Sumo/Refrigerante |
| 3.4) Consome alimentos açucarados (bolos/doces)? ☐ Todos os dias ☐ Regularmente ☐ Raramente ☐ Nunca |
| 3.5) Com que regularidade consome fruta? ☐ Todos os dias ☐ Regularmente ☐ Raramente ☐ Nunca |
| 3.6) Com que regularidade consome fritos? ☐ Todos os dias ☐ Regularmente ☐ Raramente ☐ Nunca |
| 3.7) Está atualmente a realizar algum tipo de dieta alimentar? ☐ Sim ☐ Não |
| Se sim, qual? |
| 3.8) É vegetariano? ☐ Sim ☐ Não |

| 4. Historial Clínico |
| --- |
| 4.1) Tem algum tipo de condição médica diagnosticada (doença/lesão/alergia)? ☐ Sim ☐ Não |
| Se sim, qual? |
| 4.2) Está a tomar algum tipo de medicação? ☐ Sim ☐ Não |
| Se sim, qual? |
| 4.3) Está atualmente com algum problema de fadiga ou dor muscular? ☐ Sim ☐ Não |
| Se sim, qual e em que zona do corpo? |
| 4.4) Neste preciso momento, está ansioso/stressado? ☐ Sim ☐ Não |

Muito obrigado pela colaboração!

# ANNEX 2 –
# WRITTEN CONSENT

## CONSENTIMENTO INFORMADO, LIVRE E ESCLARECIDO PARA PARTICIPAÇÃO EM INVESTIGAÇÃO

*Por favor, leia com atenção a seguinte informação. Se achar que algo está incorrecto ou que não está claro, não hesite em solicitar mais informações. Se concorda com a proposta que lhe foi feita, queira assinar este documento.*

**Título do estudo**: Muscle Fatigue Assessment in Manual Handling of Loads using Motion Analysis and Accelerometers

**Enquadramento**: Tese de Mestrado do Mestrado em Engenharia de Segurança e Higiene Ocupacionais (MESHO), realizado na FEUP e orientada pela Professora Doutora Joana Cristina Cardoso Guedes.

**Explicação do estudo**: O principal objetivo do estudo é avaliar a fadiga muscular durante o transporte manual de cargas recorrendo a análise de movimento e a acelerómetros. O estudo será iniciado com o preenchimento de um breve questionário que aborda 4 tópicos, nomeadamente dados pessoais, estilo de vida, hábitos alimentares e historial clínico. De seguida serão ligados acelerómetros e sensores de força nos membros superiores do voluntário, que irá realizar um movimento repetitivo de elevação de uma carga de 2,5 kg entre 2 prateleiras a diferentes alturas, até à sua exaustão voluntária, isto é, até não conseguir realizar mais a tarefa descrita. Enquanto realiza a tarefa, serão utilizadas câmaras de vídeo para gravar os movimentos realizados durante toda a experiência, sendo que estas imagens serão posteriormente analisadas e correlacionadas com os dados de aceleração recolhidos pelos acelerómetros. Um metrónomo irá marcar o passo a que os voluntários devem realizar os movimentos de elevação e descida da carga, de forma a que todos os voluntários executem a tarefa em iguais condições.

**Condições e financiamento**: Este estudo não acarreta qualquer tipo de custos ao voluntário nem prejudicará a sua saúde e condição física. Uma vez que a sua participação é voluntária, pode retirar-se a qualquer altura ou recusar participar, sem que tal facto tenha consequências para si.

**Confidencialidade e anonimato**: Toda a informação recolhida será confidencial e não será revelada a terceiros. Os dados recolhidos serão utilizados apenas no presente estudo. A identificação dos participantes nunca será tornada pública.

Agradeço o tempo despendido na leitura do presente documento.

**Aluno:** Fábio Gabriel Pereira Bernardo **E-mail:** --------------------------- **Telemóvel:** ---------

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*Declaro ter lido e compreendido este documento, bem como as informações verbais que me foram fornecidas pela pessoa que acima assina. Foi-me garantida a possibilidade de, em qualquer altura, recusar participar neste estudo sem qualquer tipo de consequências. Desta forma, aceito participar neste estudo e permito a utilização dos dados que de forma voluntária forneço, confiando em que apenas serão utilizados para esta investigação e nas garantias de confidencialidade e anonimato que me são dadas pelo/a investigador/a.*

Nome: … … … … … … … …... … … … …... … … … … … … … … … … …

Assinatura: … … … … … … … …... … … … … ... … … … … … … … … … … Data: …… /…… /………..

**ESTE DOCUMENTO É COMPOSTO DE 1 PÁGINA E FEITO EM DUPLICADO:**

**1 VIA PARA O INVESTIGADOR E 1 PARA A PESSOA QUE CONSENTE**